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1 OF 3
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Comprehensive Study of Water
and Related Land Resources

Puget Sound and Adjacent Waters

State of Washington

Appendix III
Hydrology and Natural Environment

Puget Sound Task Force—Pacific Northwest River Basins Commission

March 1970

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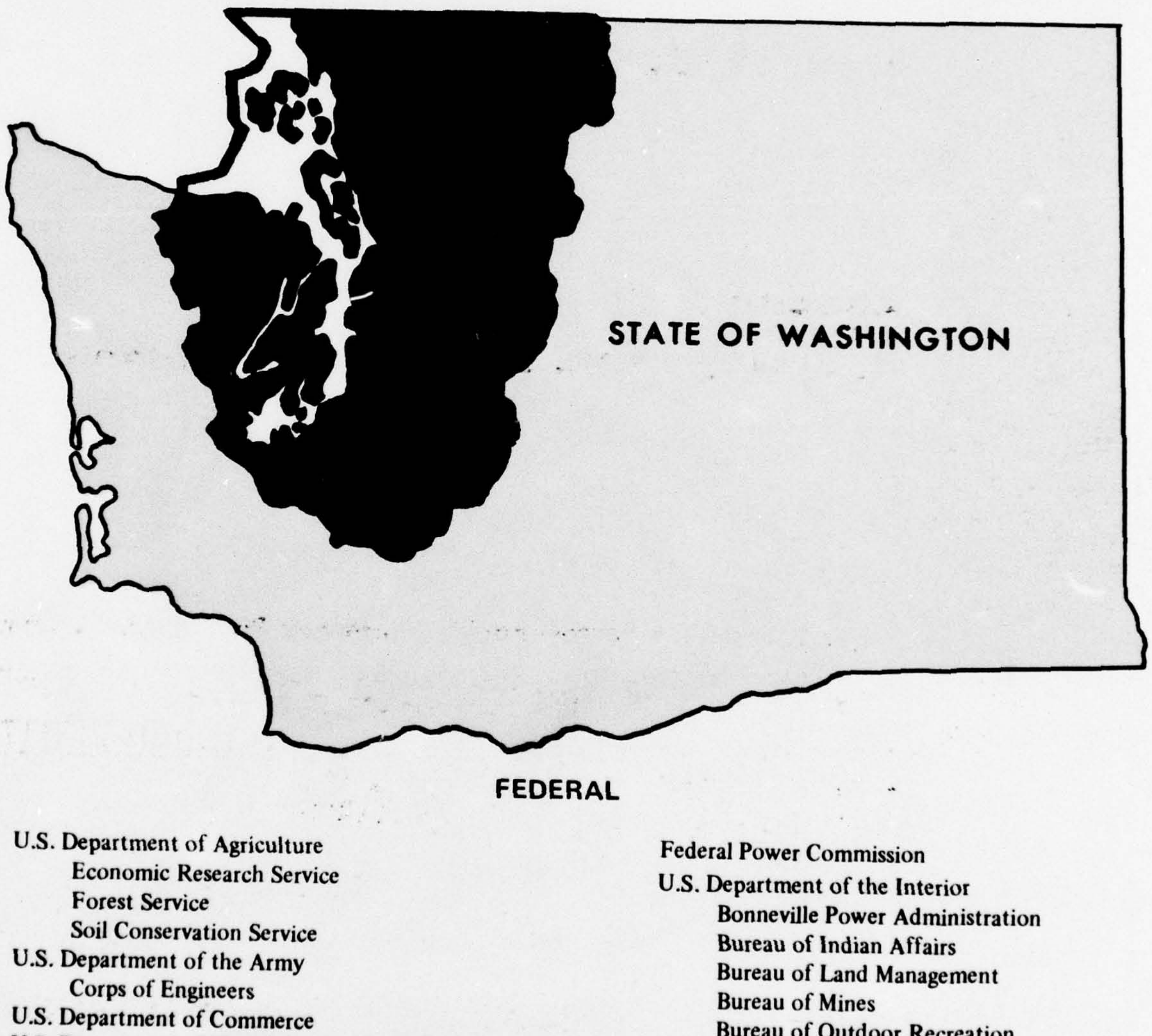

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6

Comprehensive Study of Water and Related Land Resources.

Puget Sound and Adjacent Waters.

APPENDIX III.

HYDROLOGY AND NATURAL ENVIRONMENT,

10

Alfred T. Neale, Sydney Steinborn,
Lewis F. Kehne, Ernest E. Allen
Francis L. Nelson

11 1970 12 222p.

Hydrologic Studies Technical Committee

PUGET SOUND TASK FORCE of the PACIFIC NORTHWEST RIVER BASINS COMMISSION

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FOREWORD

APPENDIX III, HYDROLOGY AND NATURAL ENVIRONMENT, contains a detailed report of one component of the Comprehensive Water Resource Study of Puget Sound and Adjacent Waters which provides supporting data for the overall water resource study.

The Summary Report is supplemented by 15 appendices. Appendix I contains a Digest of Public Hearings. Appendices II through IV contain environmental studies. Appendices V through XIV each contain an inventory of present status, present and future needs, and the means to satisfy the needs, based upon a single use or control of water. Appendix XV contains the formulation of basin plans.

River-basin planning in the Pacific Northwest was started under the guidance of the Columbia Basin Inter-Agency Committee (CBIAC) and completed under the aegis of the Pacific Northwest River Basins Commission. A Task Force for Puget Sound and Adjacent Waters was established in 1964 by the CBIAC for the purpose of making a water resource study of the Puget Sound based upon guidelines set forth in Senate Document 97, 87th Congress, Second Session.

The Puget Sound Task Force consists of ten members, each representing a major State or Federal agency. All State and Federal agencies having some authority over or interest in the use of water resources are included in the organized planning effort.

The published report is contained in the following volumes.

SUMMARY REPORT

APPENDICES

I. Digest of Public Hearings
II. Political and Legislative Environment
III. Hydrology and Natural Environment
IV. Economic Environment
V. Water-Related Land Resources
   a. Agriculture
   b. Forests
   c. Minerals
   d. Intensive Land Use
   e. Future Land Use
VI. Municipal and Industrial Water Supply
VII. Irrigation
VIII. Navigation
IX. Power
X. Recreation
XI. Fish and Wildlife
XII. Flood Control
XIII. Water Quality Control
XIV. Watershed Management
XV. Plan Formulation

APPENDIX III
HYDROLOGY AND NATURAL ENVIRONMENT

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FIGURES

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INTRODUCTION

Rugged mountains and glaciers, drift plains and fertile valleys, tumbling streams and large meandering rivers discharging into an inland sea, are a few of the many features that make up the complex land and water resources of the Puget Sound Area. A description of this natural environment as characterized through physical geography, climatology, and hydrology is presented in this, the Hydrology and Natural Environment Appendix. In this volume are summarized most of the hydrologic and climatologic data available for the Puget Sound Area at the time of the study (1966).

A broad, general portrayal of the land resources is given in the Physical Geography chapter. This portrait begins with a description of the land forms as they now exist, follows with discussions of the type and characteristics of soils, and concludes with a statement about the natural cover that has developed in the climate of the region. The major river-basins are listed in this chapter. Soils and cover are developed in much more detail in Appendix V Water-Related Land Resources.

The collective state of the earth's atmosphere over the Puget Sound region during 1930-1960 is discussed in the Climatology chapter. Precipitation, temperature, humidity, wind intensity and direction are the major parameters used to define the climate.

Surface and ground-water resources are described in detail in the Hydrology chapters. Streamflow characteristics of the major rivers in the 11 sub-basins of the Puget Sound Area are discussed in terms of quantity and quality. Most hydrologic data in the region consists of streamflow records which are analyzed in this presentation to describe the quantitative characteristics of surface water. In analyzing the surface-water data a standard 30 year period, 1931-1960, is used in this report. Ground-water occurrence, yields, and quality are also described for each basin to the extent permitted by the data available.

The appendix concludes with a discussion of needed hydrologic investigations. These investigations are required to meet long-range hydrologic needs revealed in the course of developing the comprehensive plans.

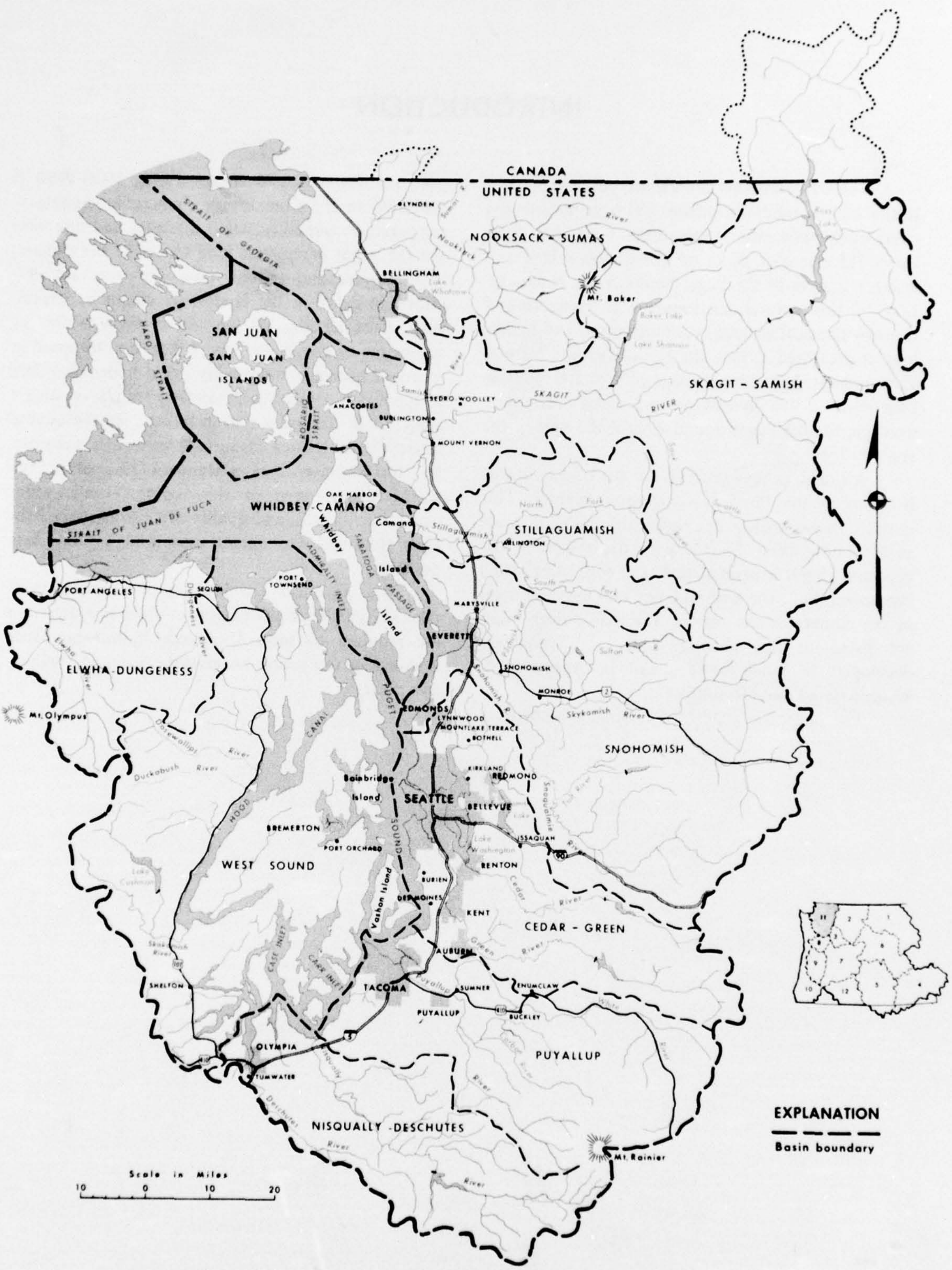
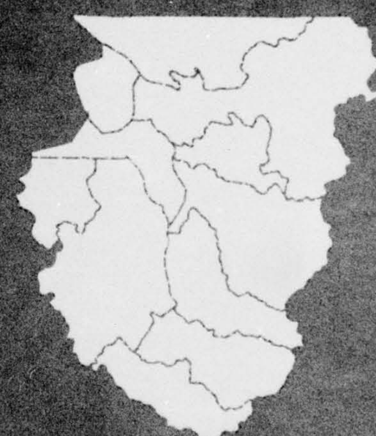


Figure 1. Basins in the Puget Sound Study Area

Physical Geography



PHYSICAL GEOGRAPHY

The physical setting of the Puget Sound Area is described in this chapter. This description includes sections on topography, geology, soils and cover, and a listing of the major river basins. This part of the appendix provides a general background with which to appreciate better the significance of the climatologic and hydrologic relationships.

The Puget Sound Area occupies the northwest corner of Washington State. It is bounded on the north by Canada, on the east by the Cascade Range, on the west by the Olympic Range, and on the south by a range of low hills. A location map of the study area together with its sub-basins is shown in Figure 1. Almost in the center of the region is Puget Sound, an inland sea with 10 major ports having access to the Pacific Ocean. The region has wild areas in the Cascade Mountains and on the Olympic Peninsula, salt-water beaches, and sheltered inlets along interior waterways. The Area provides productive agricultural land, adequate sites for industry, abundant water supplies, and extensive forests.

TOPOGRAPHY

Within the 15,900 square-mile Puget Sound Area, striking contrasts in the type of terrain result in wide variations in the region's water resources. The lowlands contrast markedly with the mountains of the Olympic and Cascade Ranges, which form the region's western and eastern borders respectively. The southern border is a low divide that separates the Puget Sound drainages from the Chehalis River basin.

Puget Sound itself is an inland sea providing a marine setting for a large part of the region. The salt-water area of about 2,500 square miles is characterized by numerous channels, bays, and inlets. South of Admiralty Inlet, the principal entrance from the Straits of Juan de Fuca, the Sound has two main branches. The western branch, Hood Canal, is a long, narrow arm extending southward about 50 miles near the base of the Olympic Mountains. The eastern branch of the Sound is considerably larger, and contains the deep-water harbors of the region's principal cities. Between the two branches is the Kitsap Peninsula, an area of 582 square miles that lies mostly below an altitude of 500 feet.

Alluviated river valleys, their broad floors bordered by bluffs and steep hills, constitute an important physiographic feature of the Puget Sound lowlands. The lowland valleys, with their mountain valley extensions, contain most of the population, industry, and agriculture in the study area. The valleys are separated by uplands whose gently rolling surfaces are altered segments of a formerly continuous plain. Terraces, lakes, and marshy depressions diversify the terrain on the uplands. In much of the area, the transition from these broad, hilly lowlands to mountains is rather abrupt.

In the Cascade Range the principal rivers head at altitudes where precipitation is abundant and large amounts of snow accumulate each winter. The higher ridges generally reach an altitude of about 8,000 feet in the north and 5,000 feet in the south. Rising prominently above the rather uniform summit levels of the Cascades are the inactive volcanoes of Mount Baker (10,778 ft.), Glacier Peak (10,541 ft.), and Mount Rainier (14,410 ft.). The 27 named glaciers on Mount Rainier constitute the most extensive glacier system of any peak in the conterminous United States. However, farther north in the Cascades, numerous smaller glaciers have a total area considerably greater than that of the glaciers on Mount Rainier.

The Olympic Mountains on the west side of the region, though generally at a lower altitude than the Cascades, are similarly rugged and scenic. Within Olympic National Park is a complex system of deep valleys and canyons, separated by sharp ridges and peaks that commonly attain altitudes of 6,000 feet. In contrast to the Cascade Range, there are no volcanic peaks in the Olympic Mountains. Streams abound; the headwaters of the largest rivers originate at glaciers and snowfields on the major peaks. To the north, relatively narrow hilly lowlands lie between the Olympic Mountains and the Strait of Juan de Fuca.

Topography has a marked influence on climate in the region. The Cascade Range and Rocky Moun-

tains shield western Washington from cold air masses that travel southward across Canada in the winter. The Olympic Mountains and the Coast Range on Vancouver Island effectively protect the area from the more intense winter storms that reach the coast from the west. The Strait of Juan de Fuca, Strait of Georgia, and the Chehalis River valley provide passages for maritime air which has a moderating influence on the climate in both summer and winter.

An area often referred to as the "rain shadow" of the Olympic Mountains extends eastward from Port Angeles almost to Everett and northward into the San Juan Islands. This is the driest section of the region–it receives an average of 15 to 30 inches of precipitation annually. Most of the winter precipitation in the Puget Sound Area falls as rain at altitudes below 1,500 feet, as rain or snow between 1,500 and 2,500 feet, and as snow at the higher elevations.

Altitude also governs the seasonal distribution of runoff: lowland streams generally carry their greatest runoff in response to rainfall during the winter, whereas high mountain streams are fed primarily by melting snow and ice during the spring and summer. Consequently, there are two patterns of seasonal runoff, one being similar to the seasonal pattern of precipitation, and the other corresponding to seasonal variations in temperature. Modifications of the two basic patterns are evident in drainage basins that contain large amounts of storage. Storage, whether in glaciers, lakes and reservoirs, or in the ground, tends to moderate the cyclic patterns of stream runoff.

GEOLOGY

Fundamental to the understanding of hydrologic processes is a basic knowledge of the geologic framework, which influences virtually all elements of the hydrologic environment. In particular, runoff, infiltration, water quality, and ground-water occurrence are influenced by the character of geologic materials.

The study area occupies a broad north-trending structural trough which attained its present form toward the close of the Tertiary Period, more than a million years ago. The east and west flanks of the trough are composed of consolidated rocks that were arched and developed into the Cascade Range and Olympic Mountains. The mountains were eroded to their present relief, and the resulting sediments accumulated in the trough during the Quaternary Period.

With the advent of the Quaternary Period, the climate became colder, and a lobe of a continental glacier moved into the lowland area from the north. The glacier was several thousand feet thick, and had the power to erode, transport, and deposit large volumes of rock material. Preglacial river valleys were scoured considerably, both in width and in depth. Much of the rock material abraded by the glacier was finely pulverized, and was incorporated into the ice mass together with various-sized rock fragments, some of which had been transported from areas north of the Puget Sound. These materials were subsequently laid down as unstratified till deposits.

Return to a warmer climate caused the glacier to melt and retreat. Streams fed by glacial melt water deposited stratified sand and gravel, termed recessional outwash. Remnants of the glacier and marginal deposits of the recessional outwash dammed the rivers, forming lakes and disrupting the drainage system considerably, as streams were diverted to form new channels. The melting of blocks of ice that had become buried in the outwash formed small depressions on outwash plains and terraces. Many of the depressions became lakes or swamps in which organic materials accumulated and later were transformed into peat. After the glacier had retreated from the region, the sedimentary processes of preglacial times resumed, and the trough again received material eroded from the surrounding highlands.

The return to a warmer climate was by no means permanent; temperatures gradually bacame lower and the region was again subjected to glaciation. Continental glaciers are believed to have advanced into and withdrawn from the study area at least four times in the Quaternary Period. During the glaciations, intermittent volcanic activity formed the prominent cones of the Cascade Range-Mount Baker, Glacier Peak, and Mount Rainier.

During each glacial event, the preglacial erosional and depositional features were at least partly destroyed or altered. Only the effects of the most recent (Fraser) glaciation, which ended in the Puget Sound Area about 10,000 years ago, are today relatively intact. Characteristic of the present postglacial terrain are numerous lakes and swales, deran-

ged drainage patterns, and broad, deeply incised valleys that imply a previous occupancy by more powerful streams than now exist in the area.

Figure 2, a generalized geologic map of the Puget Sound Area, shows the areal distribution of unconsolidated sedimentary units, of Quaternary age, which contain most of the ground water in the region. These sediments seem to be thickest in the shoreline area—at least 2,800 feet thick near Sequim—and they thin to a featheredge where they lap onto outcrops of older consolidated rocks.

On valley floors the sediments are postglacial alluvial deposits associated with flood plains and deltas of the modern drainage system. Composition and texture of the alluvium are not uniform and are influenced by factors such as stream gradient and the presence of silt in melt water from alpine glaciers. Therefore, the suitability of alluvium as a water-yielding material (aquifer) varies not only from one valley to the next, but also with depth and location within a particular valley.

Many of the uplands are covered by till which, because of its compact character, favors runoff, impedes infiltration, and is not adequate for supporting large-yielding wells. Recessional outwash generally occurs in low-lying areas adjacent to the till-covered uplands; it also blankets till deposits in many places. Recessional outwash is composed mostly of sand and gravel, and areas covered with this material characteristically have rather high rates of infiltration. Large amounts of water may be stored in recessional outwash to form aquifers of high yield in areas where appreciable thickness of sand and gravel occur. Many of the streams that drain outwash areas are "naturally" regulated, and have significantly less seasonal and year-to-year variation in discharge than streams that drain lands underlain by finer grained materials. Quaternary units older than the most recent till comprise an incredibly complicated assortment of marine, lake, stream, and glacial-drift deposits. In general, these deposits contain the most dependable aquifers in the study area. Outcrops of these older units are small in areal extent, and occur principally along the bluffs that border the larger valleys and inlets.

SOILS AND COVER

The soil mantle and its vegetative cover is of special hydrologic significance in the Puget Sound Area because of the climatic and topographic features that exist. Dense vegetative cover of forest or grass tends to regulate runoff and streamflow and the root systems of the vegetation tend to maintain the maximum infiltration rate and storage capacity of the soils. Undisturbed soils under such conditions have a large pore space and heavy surface protection of litter.

Changed soil cover directly affects the flow pattern of the streams, the erosion hazard, and the amount and form of flood protection measures required. The permeability and water retention of the soil cover are of hydrologic importance, as is its stability, since soil erosion is the source of most fluvial sediment.

THE SOIL RESOURCE

Soil is the product of many centuries of physical, chemical, and biological action on rock and organic materials. Materials from which soils of the area are derived may be classified in four broad categories. These include glacial, lacustrine, and organic deposits, as well as detritus weathered from intrusive, extrusive, and sedimentary rocks.

The characteristics of a soil at any particular place are determined by (a) physical and mineral composition of the parent material, (b) climate under which the soil developed and accumulated, (c) relief, which influences drainage, moisture content, aeration, susceptibility to erosion, and exposure to sun and the elements, (d) biological forces acting upon soil material, such as plants and animals living in and on the soil, and (e) the length of time that the physical, chemical, and biological forces have been acting upon the soil-forming materials.

The parent rocks that have contributed to soil formation in the study area include a wide variety of bedrock and unconsolidated sediments. Glacial sediments consist either of compacted or cemented materials, or of loose outwash sand and gravel. Flood-plain and alluvial soils were formed from debris eroded and carried from upland areas to the valley floors by flood waters. Organic soils have their source in lakes, shallow slackwater stream channels, and bays. Such soils in the Pacific Northwest have

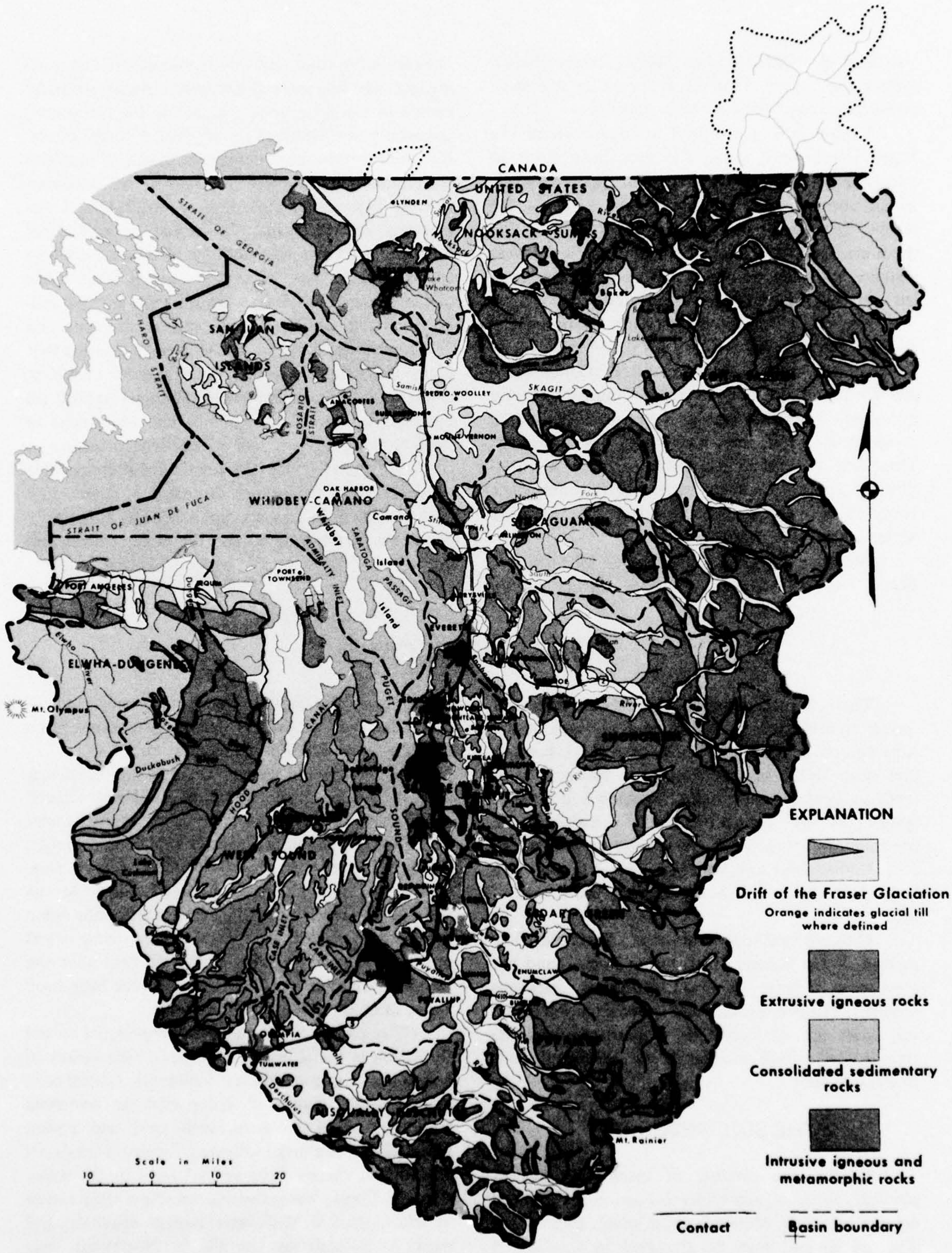


FIGURE 2. Generalized geologic map of the Puget Sound Study Area

accumulated at the rate of about 1 inch in 40 years (Hansen, 1947).

More than 1,200 soil units have been identified and classified in the Puget Sound area. Each unit is characterized by properties that help to determine the suitability of land for different uses. The various land uses include agriculture, forestry, water management, urban and industrial development, wildlife, and recreation. Many of these interpretations are discussed in other appendices or elsewhere in connection with land use and agriculture.

LAND COVER

The undisturbed land cover of the Puget Sound area is dominated by dense conifer forests. Some grass covered prairie-like areas are found in lowland parts of the Puget Sound Basin where precipitation, soil moisture and temperature create an environment less favorable to forest growth. Also, park-like areas occur at high elevations near the timberline.

The forest regeneration and growth is related to the soil type. Douglas-fir is the primary tree species. It grows extensively on well-drained soils and also on somewhat excessively drained soils. Areas opened by clear-cutting and fire promote the restocking of Douglas fir. Similarly, western white pine, Douglas-fir and lodgepole pine restocking occurs in the dry soils of the Hood Canal area. The imperfectly and poorly drained soils have a soil moisture environment suited to western hemlock, western red cedar and several species of hardwood. At the lower elevations, dense red alder stands frequently invade logged areas and remain until their short-term cycle is completed or the stands are overtopped by the conifers from the understory. Lodgepole pine grows in poorly drained soils at both low and high elevations, but rarely occurs as stands at intermediate elevations. Restocking of logged or burned areas at higher altitudes is primarily by hemlocks or true firs. Big-leaf maple, red alder, and willow occur frequently in the less dense conifer stands throughout the lower elevations. Black cottonwood is found on bottom land which is subject to periodic flooding.

The lesser vegetative ground cover varies with soil moisture and available light. Generally, a large variety of small trees, shrubs, forbs and grasses form a dense ground cover except under the most dense conifer stands. Usually this cover reestablishes quickly following any temporary ground disturbance. Ferns, mosses and shrubs are a common component, particularly on north slopes and within red alder and older conifer stands.

Vegetative cover of the prairie-like areas consists primarily of grasses. However, these areas are interspersed with scattered stands of Douglas-fir and Oregon white oak. Scotch broom and other shrubs have invaded parts of these areas. The park-like areas below timberline consist of alpine meadows of forbs, grasses and shrubs, and above timberline the ground cover blends into a mixture of heather, sedges, shrubs and low-flowering plants.

Tidal marshes have a seashore salt-grass cover, and fresh water marshes commonly have cover consisting of cattails, rushes and sedges.

Native vegetation has been removed from the fertile soils of many valley bottoms, and these areas are now used for intensive production of grass for dairy cattle, or other crops, such as vegetables and berries. Some land has also been cleared for the production of livestock forage on adjacent valley terraces and moderately rolling uplands.

The type of agriculture practiced usually conforms with the natural hydrologic balance wherein much of the cropland is devoted to forage production. About 75% of the approximately 591,000 acres developed for crops in the study area is in rotation grass, and the remainder is in vegetables, cane fruits, and specialty crops. Advantageous utilization of climate and soil produces high yields of forage and minimizes the soil erosion hazard.

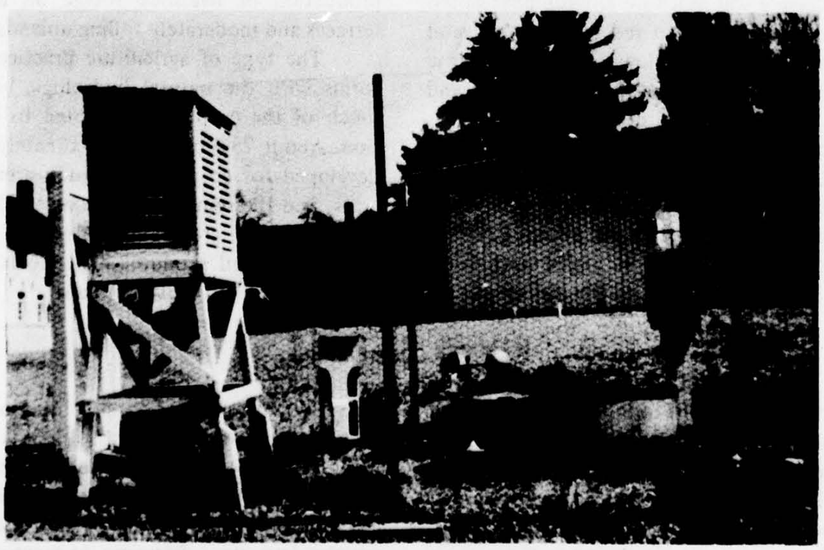
RIVER BASINS

Many rivers, large and small, flow into Puget Sound and other marine waters in the study area. The Principal streams are shown in Figure 1. The 10 river basins with the largest average runoff are as follows:

Nooksack River	Green River
Skagit River	Puyallup River
Stillaguamish River	Nisqually River
Snohomish River	Skokomish River
Cedar River	Elwha River

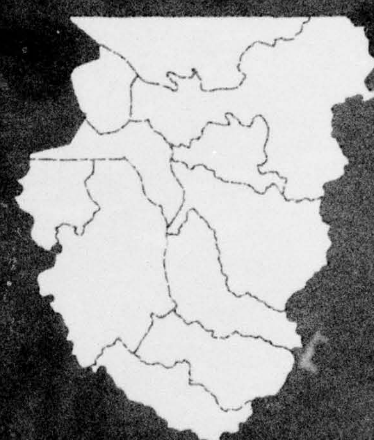
The importance of these 10 rivers is shown by the fact that they discharge, on the average, 84% of the total runoff in the Puget Sound Area. Other rivers are also important, however, in meeting many of the water needs in the other parts of the region.

Depth and water content of snow samples taken in late winter aid in forecasting of stream flows for spring and early summer. U.S.G.S. Photo.



Weather Observing Station includes rain gage, evaporation pan, anemometer and instrument shelter for exposing thermometers.

Climatology



CLIMATOLOGY

REGIONAL ENVIRONMENT

Because most of the air masses that reach the Puget Sound Area originate over the Pacific Ocean, the climate of the Area is predominately a mid-latitude, west-coast, marine type. The maritime air has a moderating influence in both winter and summer; it produces a well-defined rainy season in winter and a dry season in summer. Only occasionally does dry continental air from the north or east reach Puget Sound.

Terrain, position and intensity of the high and low pressure systems over the North Pacific, and westerly winds, as well as distance and direction from the ocean, have an influence on climate in the region. To the east, the Cascade and Rocky Mountains shield Western Washington from cold winter air masses traveling southward across Canada. To the west, the Olympic Mountains and the Coast Range on Vancouver Island effectively protect this area from the more intense winter storms reaching the coast. The Strait of Juan de Fuca, Strait of Georgia, and the Chehalis River Valley provide low level passages for maritime air moving inland.

Elements of climate that are described in the following paragraphs are precipitation, temperature and humidity, cloud cover and solar radiation, winds, and evaporation. Most of these elements are observed at the weather stations listed in Table 1 and shown in Figure 3.

TABLE 1.—Average monthly and annual precipitation, in inches, at weather stations

Area-Station	Elevation (ft)	Period of Record	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Annual
PUGET SOUND LOWLANDS															
Clearbrook	64	1931-60	5.75	4.52	4.47	3.18	2.63	2.58	1.46	1.58	2.92	5.27	5.72	6.74	46.82
Coupeville 1S	50	1931-60	2.01	1.59	1.62	1.12	1.25	1.31	.67	.69	1.19	1.73	2.25	2.30	17.73
Everett	99	1931-60	4.45	3.58	3.33	2.39	2.26	2.25	.93	1.12	1.98	3.54	4.55	4.86	35.24
Grapeview	20	1931-60	8.33	6.56	5.51	3.24	1.96	1.62	.75	.94	2.04	5.16	7.61	9.29	53.01
Monroe 2WSW	120	1931-60	6.03	5.01	4.59	3.21	3.01	2.53	1.04	1.34	2.49	4.65	6.32	6.54	46.76
Olga 2SE	80	1931-60	4.04	2.94	2.51	1.65	1.35	1.51	.88	.95	1.61	3.04	3.91	4.39	28.78
Olympia AP	195	1931-60	7.85	6.62	5.40	2.96	2.01	1.79	.76	.89	2.09	5.28	7.67	9.05	52.37
Port Angeles	99	1931-60	3.87	3.06	1.99	1.08	.89	.96	.48	.58	1.10	2.48	3.77	4.[illegible]5	24.61
Puyallup Exp. Sta.		1931-60	5.63	4.66	4.14	2.64	2.02	1.81	.81	.96	2.03	3.95	5.45	6.40	40.50
Quilcene 2SW	123	1931-60	8.09	6.51	4.40	3.07	2.52	2.40	.98	1.01	1.49	3.84	7.26	9.41	50.98
Seattle-Tacoma AP	386	1945-60	5.73	4.24	3.79	2.40	1.73	1.58	.81	.95	2.05	4.02	5.35	6.29	38.94
Sedro Woolley	56	1931-60	5.57	4.33	4.65	3.30	2.56	2.78	1.33	1.38	3.01	4.91	5.87	6.38	46.07
Sequim	180	1931-60	2.18	1.73	1.30	.93	.97	1.15	.47	.59	.95	1.57	2.31	2.66	16.81
Shelton	22	1931-60	10.37	8.06	6.83	3.89	2.21	1.73	.80	1.06	2.32	6.09	9.26	11.67	64.29
CASCADE & OLYMPIC FOOTHILLS															
Buckley 1NE	685	1931-60	5.59	4.71	4.94	3.86	3.13	3.36	1.25	1.41	2.77	5.15	6.23	6.91	49.31
Cushman Dam	760	1931-60	16.65	12.31	10.41	6.07	3.33	2.44	1.28	1.38	3.74	9.73	14.73	18.18	100.25
Darrington R.S.	550	1931-60	11.79	9.37	8.13	5.30	3.43	3.20	1.36	1.50	3.92	8.33	11.14	13.14	80.51
Skykomish R.S.	933	1935-43	8.80	9.56	8.04	5.51	5.01	3.49	1.21	1.32	2.77	7.37	11.66	15.27	80.01
Snoqualmie Falls	440	1931-60	7.85	6.35	6.14	4.00	3.20	3.21	1.29	1.43	3.18	6.15	8.38	9.12	60.30
WEST SLOPE CASCADES															
Cedar Lake	1,560	1931-60	13.11	10.52	11.17	7.69	6.00	5.53	2.17	2.57	5.54	10.52	13.80	15.61	104.23
Diablo Dam	891	1931-60	10.29	8.55	6.78	4.44	2.48	2.07	1.24	1.33	3.49	8.03	10.54	12.32	71.56
Electron Hdwrks	1,730	1944-60	8.93	7.73	6.62	5.33	4.12	4.12	1.45	1.68	3.51	7.66	9.80	10.79	71.74
Greenwater	1,708	1939-65	7.33	6.45	5.39	4.46	3.36	3.06	1.12	1.58	3.57	6.09	8.72	9.16	60.29
Longmire R.S.	2,762	1931-60	10.92	8.98	8.32	5.11	4.12	3.63	1.35	1.75	3.92	8.63	11.91	13.79	82.43
Palmer 3SE	895	1931-60	11.23	9.38	10.33	7.54	5.81	5.35	2.20	2.49	5.21	9.30	11.95	13.75	94.54
SUMMIT CASCADES															
Mount Baker	4,150	1927-51	11.86	10.61	12.12	8.52	6.39	4.73	3.32	3.19	7.64	11.34	13.14	16.99	109.85
Paradise R.S.	5,550	1920-60	14.89	11.22	10.64	6.45	4.71	4.54	1.70	2.72	6.12	10.93	14.44	16.61	104.97
Snoqualmie Pass	3,020	1930-59	14.77	12.74	11.72	6.39	4.68	4.86	1.67	2.03	4.81	10.46	15.41	18.06	107.60
Stampede Pass	3,958	1944-60	12.03	10.15	10.60	5.60	4.25	4.09	1.46	2.04	4.39	8.81	12.58	16.19	92.19
Stevens Pass	4,085	1939-64	11.26	8.57	7.94	4.65	3.59	2.89	1.35	1.70	4.06	7.32	11.25	12.17	76.75

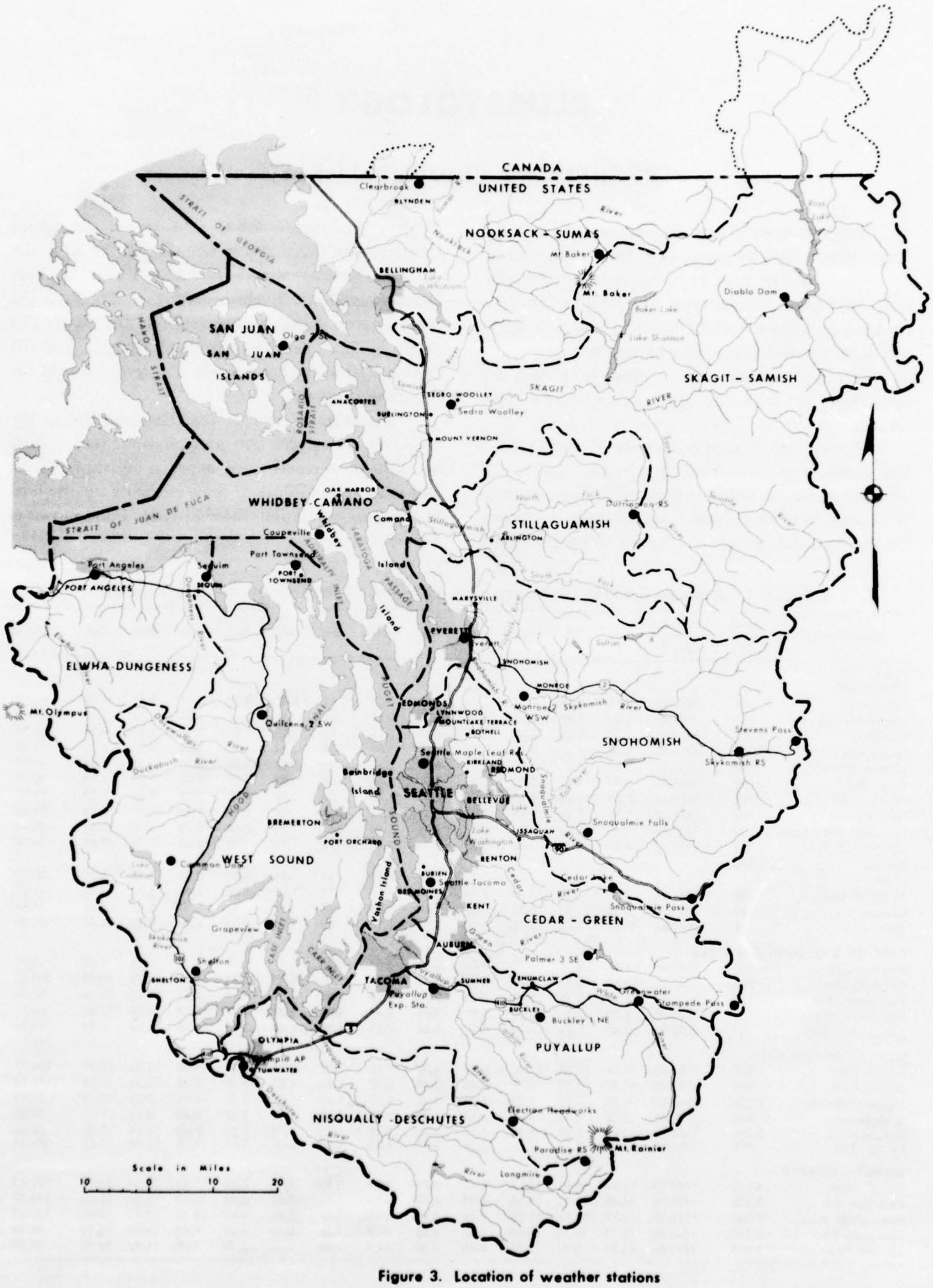


Figure 3. Location of weather stations

PRECIPITATION

Maritime air reaching the Washington coast in late fall and winter is moist, and its temperature is near that of the ocean's surface. Orographic lifting and cooling as air masses move inland result in persistent cloudiness and widespread precipitation patterns in the Puget Sound Area. Precipitation is light in summer, increasing in fall, reaching a peak in winter, then decreasing in spring (Fig. 4). Normally, a slight increase in precipitation in May and June is followed by a sharp drop near the first of July. Fifty percent of the annual precipitation falls in the 4-month period October through January, and 75% occurs in the 6 months October through March. Rainfall for July and August is less than 5% of the annual total.

The driest section in the region, often referred to as the "rain shadow" of the Olympic Mountains, receives 15 to 30 inches of precipitation. This dry belt extends eastward from Port Angeles almost to Everett, and northward into the San Juan Islands. Frequently, a drizzle or light rain falls on this area while other localities are receiving moderate rainfall. Annual precipitation ranges from 35 to 50 inches over most of the lowlands, increasing to 75 inches in the foothills and from 100 to more than 200 inches on the wettest slopes of the Cascade and Olympic Mountains (Fig. 5).

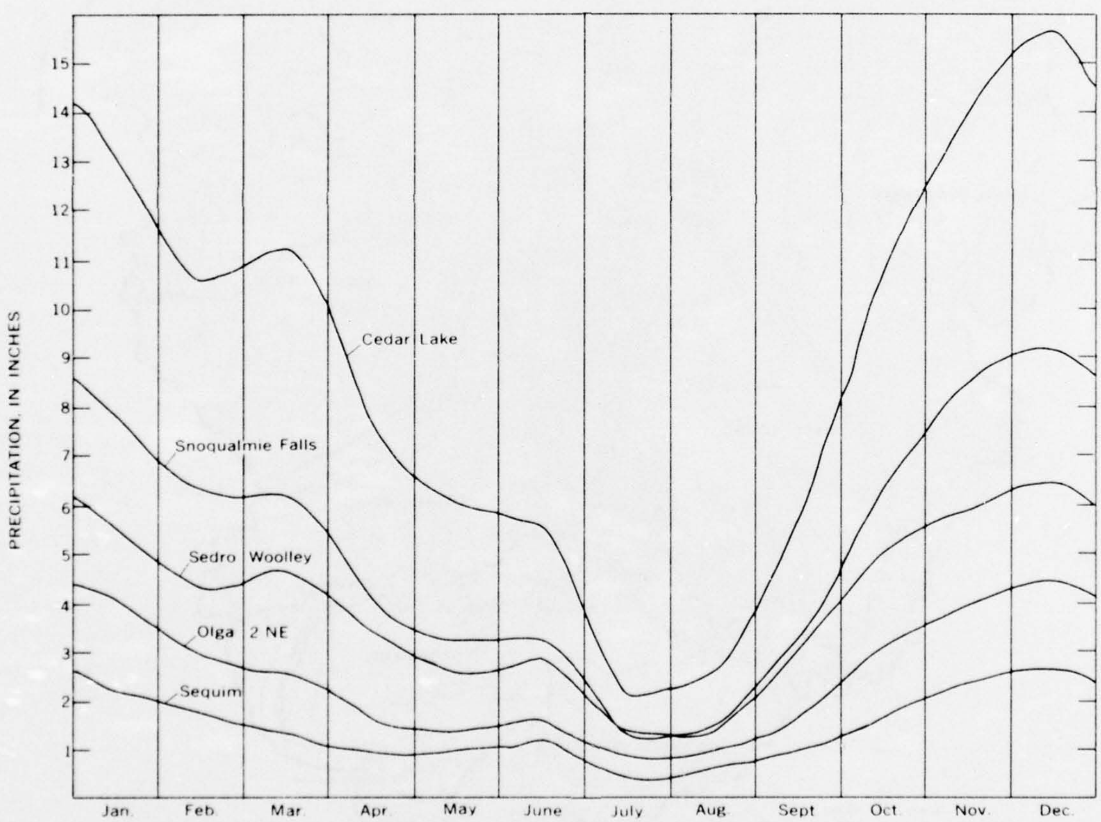


FIGURE 4.—Average monthly precipitation at selected stations.

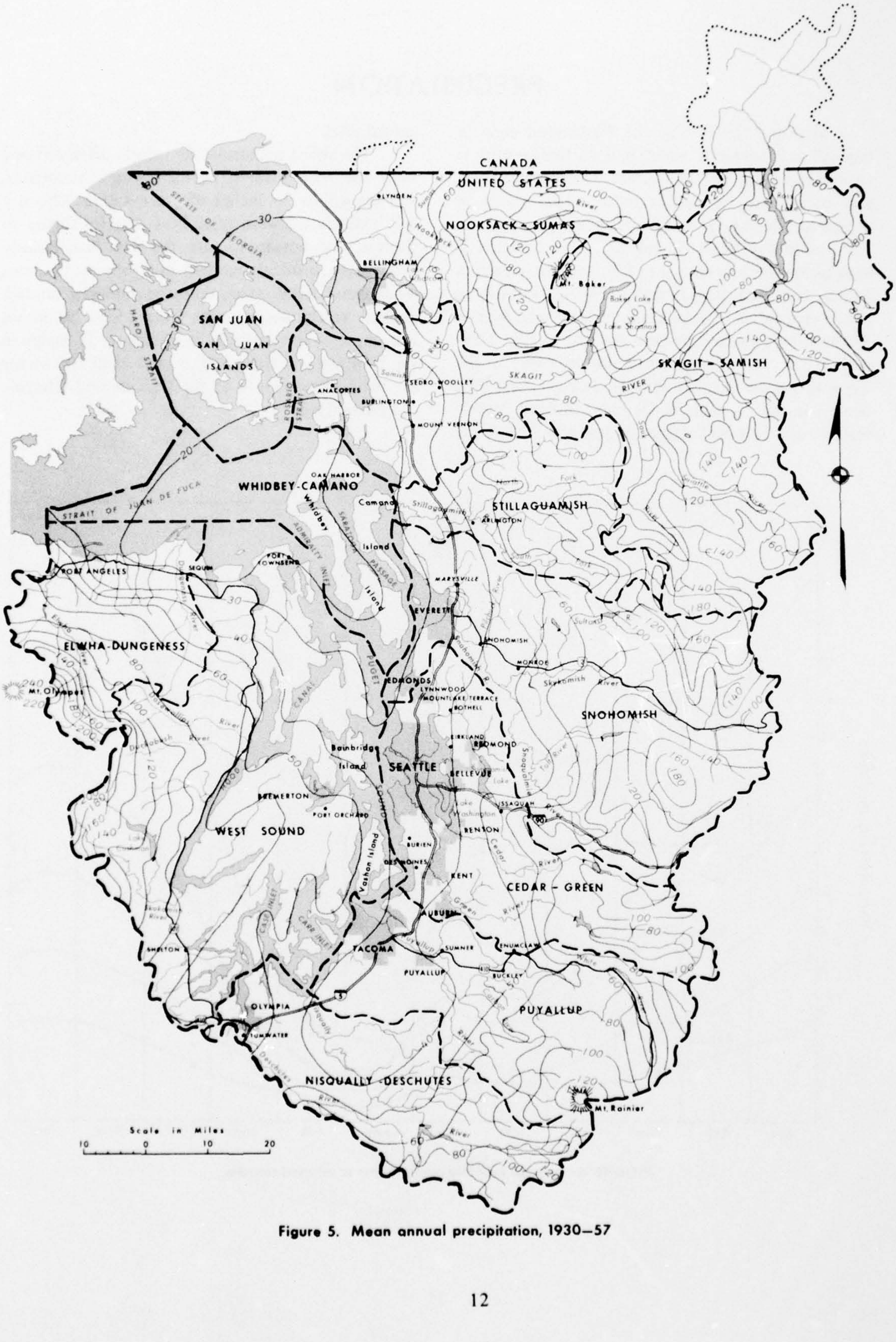


Figure 5. Mean annual precipitation, 1930–57

TABLE 2.—Monthly precipitation, in inches, that is exceeded 10 percent and 90 percent of the time at selected weather stations

Area/Station	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Annual
PUGET SOUND LOWLANDS													
Clearbrook													
Low (90 percent)	1.6	2.7	2.4	1.5	1.1	.7	Tr	.3	1.3	2.4	2.0	3.9	35.9
High (10 percent)	9.1	7.4	7.9	4.9	4.1	5.4	2.9	4.2	5.9	8.1	8.9	10.2	57.6
Coupeville 1S													
Low (90 percent)	1.1	.8	1.0	.4	.3	.2	Tr	.1	.4	.7	.9	1.1	13.7
High (10 percent)	3.0	2.6	2.4	1.7	2.6	2.6	1.4	1.6	2.8	3.0	3.7	3.4	21.7
Monroe 2WSW													
Low (90 percent)	3.1	1.8	2.5	1.2	1.3	.5	.1	.7	.4	2.3	2.8	3.5	35.5
High (10 percent)	8.6	8.3	7.5	4.9	5.1	5.1	2.4	2.5	5.4	8.6	9.9	8.6	56.7
Olga 2SE													
Low (90 percent)	1.5	1.5	1.1	.5	.3	.1	Tr	.2	.5	1.2	1.4	1.8	20.1
High (10 percent)	5.9	4.8	3.8	2.6	2.7	3.3	1.5	2.2	3.4	5.2	6.5	6.6	35.5
Olympia AP													
Low (90 percent)	3.0	3.9	2.3	.5	.3	.1	Tr	Tr	.3	2.8	2.3	3.8	33.5
High (10 percent)	12.0	11.3	8.3	4.7	3.5	3.4	2.0	1.7	3.9	9.5	12.4	12.1	65.3
Puyallup Exp. Sta.													
Low (90 percent)	1.8	2.4	2.1	.6	.6	.2	Tr	.1	.5	1.9	1.9	3.2	26.9
High (10 percent)	9.2	7.7	6.7	4.4	4.2	4.3	1.5	1.9	3.7	6.8	9.9	8.5	52.0
Quilcene 2SW													
Low (90 percent)	2.6	2.2	1.2	1.0	.7	.8	.1	.2	.2	1.1	2.3	3.4	34.1
High (10 percent)	15.0	11.7	8.2	5.4	5.3	4.7	2.2	2.6	3.1	8.5	13.8	18.6	63.8
CASCADE & OLYMPIC FOOTHILLS													
Buckley 1NE													
Low (90 percent)	2.6	2.2	2.4	1.1	1.3	.7	.1	.3	1.0	2.3	2.1	3.6	36.9
High (10 percent)	8.2	7.4	7.1	6.4	5.2	7.1	2.8	3.1	5.2	8.9	11.5	10.0	63.3
Cushman Dam													
Low (90 percent)	6.6	6.9	5.3	.8	.8	.3	.1	.2	.6	4.6	4.0	10.8	73.6
High (10 percent)	30.2	19.6	18.1	10.7	6.8	6.6	2.9	3.2	8.5	18.4	25.3	29.0	126.7
Darrington R.S.													
Low (90 percent)	3.4	4.9	4.8	1.3	1.0	.7	.1	.4	1.0	2.8	3.7	6.9	59.8
High (10 percent)	19.4	15.3	12.7	8.8	6.5	6.7	3.0	2.9	8.6	14.6	18.0	18.7	102.9
Snoqualmie Falls													
Low (90 percent)	3.1	2.9	3.5	1.1	1.0	.8	.1	.6	.6	2.5	3.1	4.7	45.1
High (10 percent)	12.1	9.4	9.7	6.8	5.3	6.8	2.9	2.9	7.2	9.9	13.9	11.8	75.3
WEST SLOPE CASCADES													
Cedar Lake													
Low (90 percent)	5.8	4.8	6.3	2.5	2.3	1.5	.1	1.2	1.7	4.6	5.8	9.0	80.0
High (10 percent)	18.9	16.4	17.4	12.2	10.8	9.7	4.4	5.6	12.7	16.7	22.2	20.0	133.0
Diablo Dam													
Low (90 percent)	3.1	2.9	3.1	1.4	.7	.7	.2	.2	.7	3.4	3.5	6.6	52.3
High (10 percent)	18.1	18.3	11.0	7.4	4.3	3.8	2.3	2.7	7.2	12.8	16.9	17.5	90.6
Longmire R.S.													
Low (90 percent)	4.5	3.5	4.2	1.8	1.8	.7	Tr	.5	1.0	2.6	3.9	7.4	57.5
High (10 percent)	16.9	12.8	13.1	7.8	7.4	6.9	3.4	4.5	7.9	14.4	19.4	18.6	103.9
Palmer 3SE													
Low (90 percent)	4.2	3.6	4.9	3.0	2.3	1.1	.2	1.2	2.1	4.6	3.7	8.3	71.6
High (10 percent)	16.5	14.7	16.0	11.6	9.4	10.5	4.9	4.7	10.6	15.6	19.0	19.1	123.2
SUMMIT CASCADES													
Paradise R.S.													
Low (90 percent)	6.7	2.8	3.7	3.2	1.6	.7	Tr	.1	1.4	3.7	2.8	9.9	70.7
High (10 percent)	24.3	16.9	18.2	10.7	9.1	10.4	5.0	6.2	19.2	23.5	26.3	24.7	137.8
Snoqualmie Pass													
Low (90 percent)	7.1	5.0	4.8	2.2	1.8	1.0	.1	.8	1.0	3.7	6.7	8.3	83.5
High (10 percent)	26.4	18.9	18.5	10.5	9.8	8.8	3.5	4.3	10.7	17.3	27.1	24.0	141.2
Stampede Pass													
Low (90 percent)	4.5	5.9	5.3	1.9	1.7	2.0	.3	.7	1.4	2.8	6.3	7.2	63.1
High (10 percent)	22.3	16.6	15.0	9.7	7.8	7.0	3.7	4.4	10.5	15.4	20.6	27.5	118.6

TABLE 3.—Predicted rainfall intensities, in inches, for various durations and recurrence intervals in lowland and upland areas

	Recurrence interval									
	Puget Sound Lowlands					West slope Cascades, SE slope Olympics and foothills				
Duration	2 yrs	5 yrs	10 yrs	25 yrs	50 yrs	2 yrs	5 yrs	10 yrs	25 yrs	50 yrs
30 minutes	0.4	0.4	0.6	0.6	0.7	0.5	0.6	0.8	0.9	1.0
1 hour	.5	.6	.7	.8	.9	.6	.8	1.0	1.2	1.4
2 hours	.7	.8	1.0	1.2	1.5	1.0	1.2	1.5	1.8	2.0
3 hours	.9	1.2	1.5	1.7	2.0	1.5	1.8	2.0	2.5	3.0
6 hours	1.5	1.8	2.0	2.5	2.8	2.5	3.0	4.0	4.5	5.0
12 hours	2.0	2.5	3.0	3.2	3.5	3.5	4.5	5.5	6.0	7.0
24 hours	2.5	3.0	3.5	4.0	4.2	4.0	6.0	7.0	8.0	10.0
48 hours	3.0	4.0	4.5	5.0	5.5	6.0	7.5	8.0	9.5	10.5
96 hours	4.0	4.5	5.5	6.0	7.0	8.0	9.0	10.0	10.5	15.0

Intensities estimated from Weather Bureau Technical Papers Nos. 28, 40, and 49.

In Figures 6-9, the variability of annual precipitation is shown for representative locations.

Table 1 shows average amounts of monthly precipitation and Table 2 shows amounts that are likely to occur 10 and 90% of the time on the average. Table 2 shows for example, at Puyallup, the total precipitation for July is on the average only a trace in one summer out of 10; also, it exceeds 1.5 inches in one summer out of 10. Annual precipitation is less than 27 inches in 1 year out of 10; also, it exceeds 52 inches in 1 year out of 10.

The probability of receiving specific amounts of precipitation in any 7-day period, based on weekly totals from 1931-60, is given in Figures 10-13. As an example, during the first week of March, the probability of receiving 0.40 inch of precipitation is 28% at Sequim, 64% at Puyallup, 81% at Sedro Woolley, and 93% at Cedar Lake.

Rainfall is usually of light to moderate intensity and is continuous over a period of time rather than heavy for brief intervals. Predicted rainfall intensities and return periods for durations ranging from 30 minutes to 96 hours are given in Table 3.

Thunderstorms occur on 5 to 15 days each year. The greater number are reported over the mountains in summer; however, they have been recorded in all localities throughout the year. Hail of sufficient size of intensity to cause damage is rarely, if ever, reported.

Most of the winter precipitation falls as rain at elevations below 1,500 feet, as rain or snow between 1,500 and 2,500 feet, and as snow at the higher elevations.

In the mountains, snow can be expected in October, and it generally remains on the ground from November until June or July. At altitudes above 8,000 feet, light snowfall in midsummer is not unusual. Total winter snowfall ranges from 10 to 30 inches over the lowlands near the Sound, 75 to 100 inches in the foothills, and 300 to 500 inches in the mountains. Average monthly and annual amounts are given in Table 4.

TABLE 4.—Average monthly and annual snowfall, in inches

AREA/STATION	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Total
PUGET SOUND LOWLANDS													
Clearbrook				T	1.1	3.7	6.8	4.0	2.1	T			17.7
Coupeville 1S				T	.5	.5	3.1	1.3	.6	T			6.0
Everett				T	.7	1.7	5.0	2.3	1.1	.2			11.0
Grapeview					.4	.3	3.5	.6	T				4.8
Monroe 2WSW				T	.8	1.1	6.0	1.4	.8	T			10.1
Olga 2SE				T	.5	.8	3.0	2.3	1.0	.1			7.7
Olympia AP				T	1.5	1.3	7.1	3.1	2.2	T			15.2
Puyallup Exp. Sta.				T	.3	.5	3.2	1.1	.3	T			5.4
Quilcene 2SW					.9	1.1	3.7	1.9	.7	.1	T		8.4
Seattle-Tacoma AP				T	1.4	2.2	6.2	2.4	2.2	T			14.4
Sedro Woolley					.7	1.6	4.1	2.1	1.6	T	T		10.1
Sequim					.7	.5	3.3	1.3	.1	T			5.9
Shelton				T	T	1.0	5.9	1.4	T	T			8.3
CASCADE & OLYMPIC FOOTHILLS													
Buckley 1NE				T	1.0	1.5	5.1	3.0	2.4	.4			13.4
Cushman Dam				T	1.3	7.0	24.0	10.0	6.2	.4			48.9
Darrington R.S.					2.0	9.7	18.0	10.6	6.5	.6			47.4
Skykomish R.S.				.3	1.4	12.7	6.7	20.8	5.0	.2			47.1
Snoqualmie Falls				T	1.4	2.6	7.8	3.6	1.4	.1			16.9
WEST SLOPE CASCADES													
Cedar Lake			T	1.0	4.3	13.8	24.7	20.0	15.2	2.9	.3		82.2
Diablo Dam				.1	5.1	16.8	23.4	16.5	9.5	.5			71.9
Electron Headworks					2.2	5.4	15.0	10.7	12.3	2.4	.1		48.1
Greenwater				.1	6.1	14.3	24.7	14.7	14.8	2.2	.1		77.0
Longmire R.S.			T	1.4	14.4	34.0	48.4	37.6	32.2	9.0	.7	T	177.7
Palmer 3SE				.3	2.5	7.7	20.0	10.7	6.6	1.0			48.8
SUMMIT CASCADES													
Mt. Baker	T		2.6	14.7	67.6	106.7	88.0	74.0	92.3	50.2	17.5	2.3	515.9
Paradise R.S.	.3	T	5.2	22.0	64.9	105.1	117.6	88.7	98.6	54.1	21.3	4.3	582.1
Snoqualmie Pass	.1		.2	7.4	40.8	84.0	96.7	88.8	74.1	22.5	5.5	.1	420.2
Stampede Pass	.1		.6	14.8	59.7	84.7	88.8	80.8	76.3	40.3	9.8	1.7	457.6
Stevens Pass	T		.5	18.6	62.1	91.2	100.4	78.4	74.4	30.8	9.9	.6	466.9

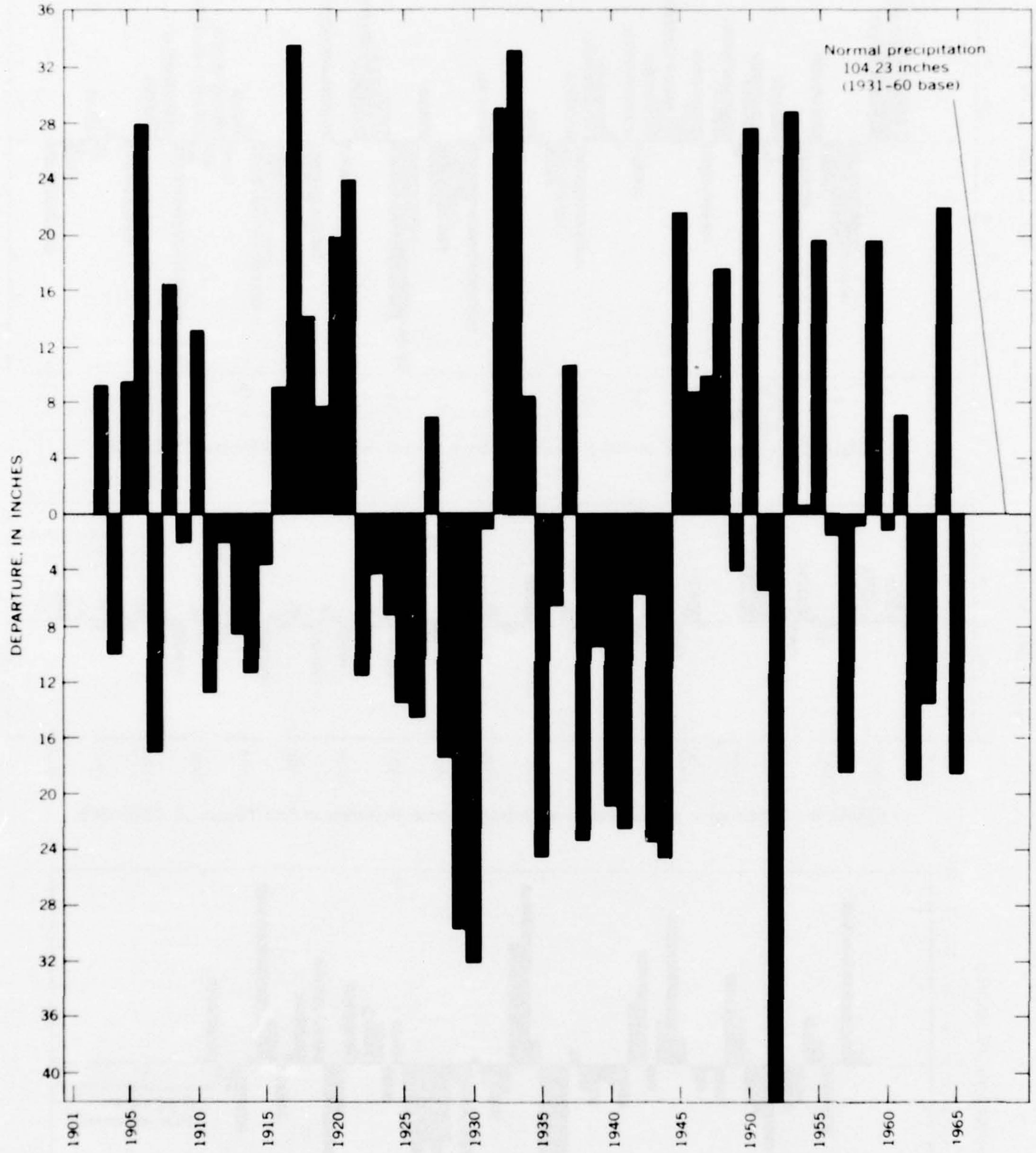


FIGURE 6.—Departure of annual precipitation from normal, in inches, at Cedar Lake, 1903-65.

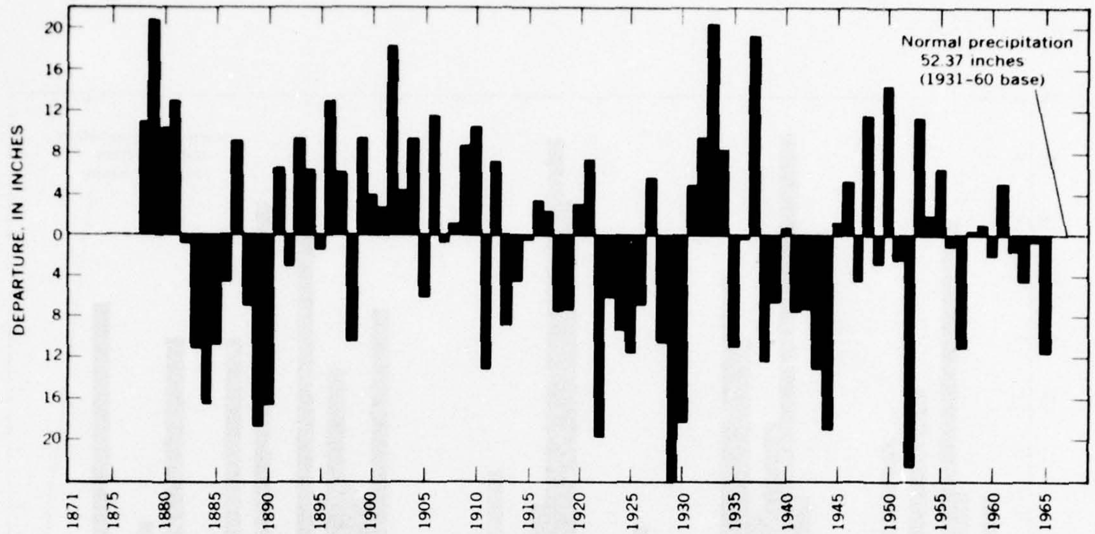


FIGURE 7.—Departure of annual precipitation from normal, in inches, at Olympia, 1878-1965.

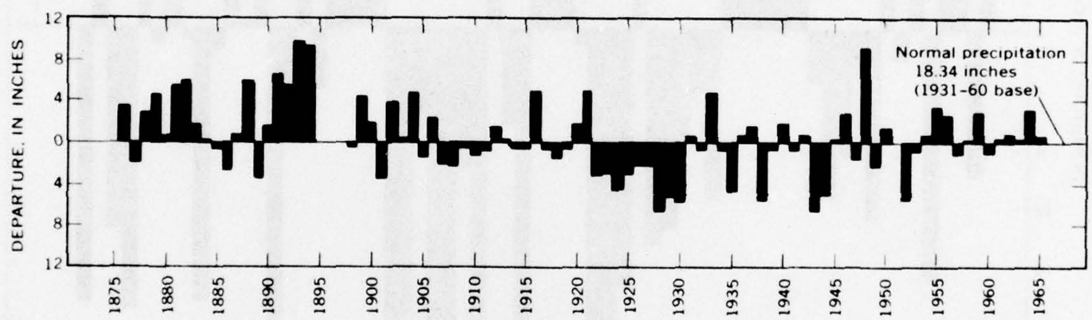


FIGURE 8.—Departure of annual precipitation from normal, in inches, at Port Townsend, 1876-1965.

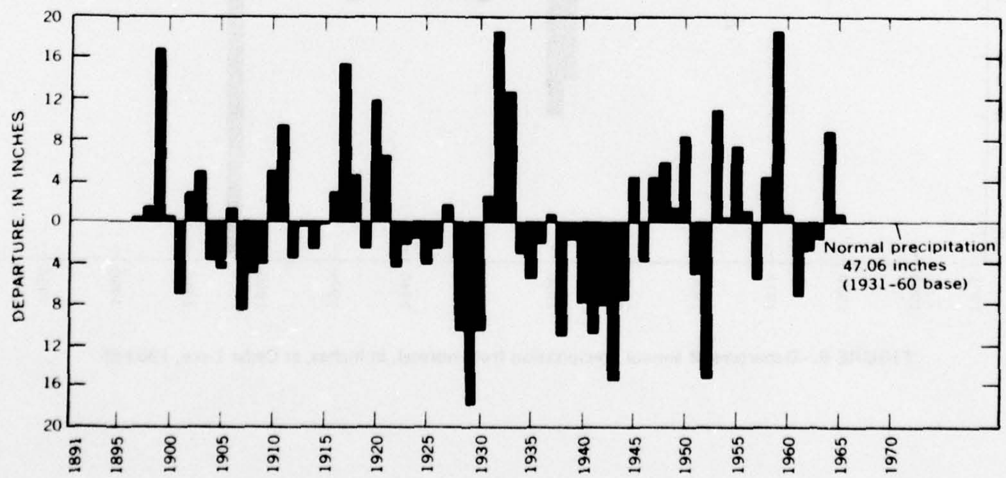


FIGURE 9.—Departure of annual precipitation from normal, in inches, at Sedro Woolley, 1897-1965.

The terrain and exposure of an area have a decided influence on the accumulation of snow on the ground. Maximum depths of accumulated snow are 15 to 30 inches over the lowlands, 30 to 50 inches in the valleys near the mountains and over the foothills, 150 to 200 inches at 3,000 feet, and 200 to 300 inches above 4,500 feet. Average, maximum, and minimum depths at selected locations are given in Table 5. In the mountains, the density of the snowpack increases from about 25% water in early winter to 45% water in April.

TABLE 5.—Snow depths, in inches, at mountain weather stations

Station	Depth	Nov		Dec		Jan		Feb		Mar		Apr		May		Jun		Jul	
		1	15	1	15	1	15	1	15	1	15	1	15	1	15	1	15	1	15
Mt. Baker 4150 feet	Average	6	26	40	59	96	109	124	140	153	164	174	168	143	116	82	45	16	4
	Maximum	24	55	140	168	190	167	234	223	276	281	298	285	264	237	216	174	120	65
	Minimum		3	T	20	28	40	43	65	60	85	72	56	20	6	T			
Greenwater 1708 feet	Average		1	1	4	7	10	12	12	10	10	4	2						
	Maximum		5	6	29	52	38	49	64	41	44	22	13						
Longmire R.S. 2760 feet	Average	1	3	5	8	18	23	28	33	33	32	27	14	6	1				
	Maximum	11	14	26	55	74	85	66	108	78	89	66	56	52	24				
Paradise R.S. 5550 feet	Average	9	25	44	63	89	109	133	146	158	172	176	170	159	135	109	74	40	11
	Maximum	54	72	100	170	140	201	204	215	274	357	327	293	259	243	192	166	132	78
	Minimum			1	16	24	30	36	70	72	81	66	68	49	22	T			
Snoqualmie Pass 3020 feet	Average	2	9	19	30	54	68	82	93	97	98	95	80	61	34	9	2	T	
	Maximum	24	23	84	116	136	122	154	168	198	195	170	153	123	98	64	29	3	
	Minimum				5	6	15	35	33	27	10	11	T						
Stampede Pass 3958 feet	Average	4	14	31	43	60	75	95	107	113	121	119	108	89	59	26	8		
	Maximum	20	55	93	119	132	128	228	202	190	216	183	186	176	149	125	84	6	
	Minimum			T	10	14	11	25	53	48	45	47	37	11					
Stevens Pass 4085 feet	Average	6	16	31	42	63	74	87	101	102	113	106	97	71	50	22	5		
	Maximum	35	47	67	64	117	140	152	166	196	200	192	170	141	126	92	59	15	
	Minimum			7	14	28	27	32	57	54	47	24	17						

TEMPERATURE AND HUMIDITY

During the warmest summer months, afternoon temperatures over the San Juan Islands and along the Sound are in the lower 70's, increasing to the upper 70's near the foothills, then decreasing into the 60's in the mountains. Temperatures reach 85°F to 90°F on 5 to 15 days per year, and extremes of 95°F to 100°F have been recorded in most of the lower valleys. The highest temperatures and lowest relative humidity accompany dry easterly winds, which seldom persist longer than 3 to 5 days. Minimum temperatures during the summer are in the 50's over the lowlands and in the 40's in the mountains. At elevations above 5,000 feet, temperatures below freezing are not unusual in midsummer.

In winter, afternoon temperatures over the lowlands range from upper 30's to mid-40's, and minimums from upper 20's to mid-30's. Below freezing temperatures are recorded on 30 to 90 nights per year, depending on air drainage, distance from the Sound, and altitude. Almost every winter, temperatures ranging from 10°F to 20°F are observed on a few nights, and below-zero readings have been recorded at many stations (Table 6).

TABLE 6.—Temperature averages and extremes, (°F), by months, at selected weather stations

AREA/STATION		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
PUGET SOUND LOWLANDS														
Clearbrook	Av. Max.	41	46	52	59	66	71	76	76	71	61	49	44	59
	Av. Min.	30	31	35	38	42	46	48	47	44	40	35	33	39
	Highest	61	65	74	86	91	96	102	98	94	84	69	62	102
	Lowest	-3	-1	9	21	28	31	34	33	28	20	8	7	-3
Everett	Av. Max.	45	48	53	59	64	68	72	72	67	60	51	47	59
	Av. Min.	33	34	37	40	45	50	52	52	48	44	38	36	42
	Highest	72	69	76	80	88	98	93	92	88	83	73	65	98
	Lowest	1	7	10	26	29	37	41	40	33	25	8	10	1

TABLE 6.—Continued

AREA/STATION		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Monroe 2WSW	Av. Max.	44	48	53	61	67	71	77	76	70	61	51	46	61
	Av. Min.	32	34	36	40	45	49	52	52	48	43	37	35	42
	Highest	72	73	77	85	92	96	99	101	94	84	72	66	101
	Lowest	-3	-2	13	24	29	34	33	39	31	23	5	10	-3
Olga 2SE	Av. Max.	44	47	51	57	63	67	70	70	66	58	50	46	57
	Av. Min.	34	35	37	40	44	47	49	49	48	44	39	36	42
	Highest	65	65	68	76	83	86	92	89	87	76	64	60	92
	Lowest	-8	5	14	28	31	37	40	42	37	26	10	14	-8
Olympia AP	Av. Max.	45	50	54	62	69	73	80	79	73	62	52	48	62
	Av. Min.	31	32	34	38	42	46	48	48	44	41	35	34	39
	Highest	63	67	75	85	92	101	103	99	95	85	74	64	103
	Lowest	0	-1	13	24	25	34	37	37	29	22	-1	12	-1
Puyallup Exp. Sta.	Av. Max.	46	50	54	62	69	72	78	78	72	62	52	48	62
	Av. Min.	31	33	35	38	43	47	49	49	46	42	36	34	40
	Highest	66	69	75	87	90	101	99	99	92	82	72	66	101
	Lowest	-3	1	12	23	25	34	38	33	30	22	0	7	-3
Sedro Woolley	Av. Max.	44	49	53	61	67	70	75	75	69	61	51	46	60
	Av. Min.	32	33	36	40	44	49	50	50	47	43	37	34	41
	Highest	67	69	75	82	90	96	94	90	91	83	71	74	96
	Lowest	-2	-1	8	25	29	34	37	36	31	20	3	4	-2
Sequim	Av. Max.	45	48	51	58	64	67	72	72	68	60	51	47	59
	Av. Min.	31	32	34	38	43	47	49	49	47	41	36	33	40
	Highest	60	66	69	80	84	91	99	94	87	76	67	63	99
	Lowest	-3	7	15	20	27	30	37	38	31	21	9	10	-3
Shelton	Av. Max.	45	49	53	61	68	72	78	77	72	62	51	47	61
	Av. Min.	32	33	35	38	43	48	51	51	47	42	36	35	41
	Highest	68	71	76	89	95	102	104	98	99	85	69	64	104
	Lowest	-2	0	17	22	25	32	36	34	32	22	5	6	-2
CASCADE & OLYMPIC FOOTHILLS														
Buckley 1NE	Av. Max.	44	48	52	59	66	70	76	75	70	59	50	46	60
	Av. Min.	32	33	35	39	43	47	50	50	47	42	37	35	41
	Highest	70	69	76	84	88	96	102	98	95	87	68	65	102
	Lowest	-3	1	10	26	30	37	37	38	33	24	2	8	-3
Cushman Dam	Av. Max.	44	47	52	60	67	72	78	78	72	62	51	46	61
	Av. Min.	31	32	34	38	44	48	51	51	49	43	37	34	41
	Highest	65	71	76	90	93	100	104	99	96	89	75	60	104
	Lowest	-2	4	15	24	29	36	40	41	34	27	8	13	-2
Darrington R.S.	Av. Max.	41	46	51	61	68	71	78	77	71	61	49	43	60
	Av. Min.	29	30	32	37	42	47	49	49	46	40	33	31	39
	Highest	74	70	78	91	100	102	104	105	102	90	77	63	105
	Lowest	-14	-11	0	20	25	31	34	33	29	19	-4	0	-14
WEST SLOPE CASCADES														
Cedar Lake	Av. Max.	39	43	47	55	61	65	72	71	66	57	47	42	55
	Av. Min.	30	31	33	37	42	46	50	50	47	42	36	33	40
	Highest	61	64	74	86	91	95	98	98	94	86	73	60	98
	Lowest	-11	0	8	25	28	35	37	35	31	20	2	10	-11
Diablo Dam	Av. Max.	37	42	48	57	66	70	78	77	71	58	45	40	57
	Av. Min.	27	29	32	37	43	48	52	52	48	41	34	31	40
	Highest	62	60	73	85	94	99	106	100	100	83	65	57	106
	Lowest	-8	-10	3	24	29	35	38	37	35	21	5	8	-10
Greenwater	Av. Max.	35	40	45	53	61	65	73	72	67	55	42	37	54
	Av. Min.	26	29	31	35	40	45	48	48	43	38	32	29	37
	Highest	59	64	73	84	91	92	102	97	91	83	65	64	102
	Lowest	-8	-5	3	26	25	30	32	33	29	24	3	1	-8
Longmire R.S.	Av. Max.	36	40	44	53	62	66	75	74	69	59	45	39	55
	Av. Min.	24	26	28	32	37	43	47	47	44	38	31	28	35
	Highest	60	64	73	83	95	95	105	100	97	88	72	60	105
	Lowest	-9	-8	-1	12	21	28	35	33	28	17	-3	-1	-9
SUMMIT CASCADES														
Mt. Baker	Av. Max.	33	36	39	43	51	56	64	66	57	50	40	35	47
	Av. Min.	21	24	26	28	36	39	44	47	41	36	29	23	33
	Highest	70	61	69	72	70	80	91	86	84	77	70	59	91
	Lowest	-12	-11	6	6	18	24	34	36	27	12	5	-6	-12
Paradise R.S.	Av. Max.	33	34	36	43	50	54	63	62	58	48	40	34	46
	Av. Min.	19	21	21	26	32	37	43	44	40	33	26	22	30
	Highest	62	62	70	70	88	86	87	92	89	79	78	62	92
	Lowest	-14	-12	-2	2	14	13	20	27	18	2	-11	-20	-20
Snoqualmie Pass	Av. Max.	32	36	43	51	58	62	70	69	64	53	40	33	51
	Av. Min.	20	22	26	31	35	40	46	46	42	35	28	24	33
	Highest	51	76	69	81	84	92	101	95	101	88	60	53	101
	Lowest	-17	-15	0	7	16	27	31	34	26	13	-6	-6	-17
Stevens Pass	Av. Max.	29	33	37	45	51	58	68	66	62	49	36	31	47
	Av. Min.	18	21	23	29	34	40	45	45	41	35	26	21	31
	Highest	53	53	70	69	80	91	95	91	87	77	56	50	95
	Lowest	-12	-10	0	11	17	28	33	30	28	22	-2	-18	-18

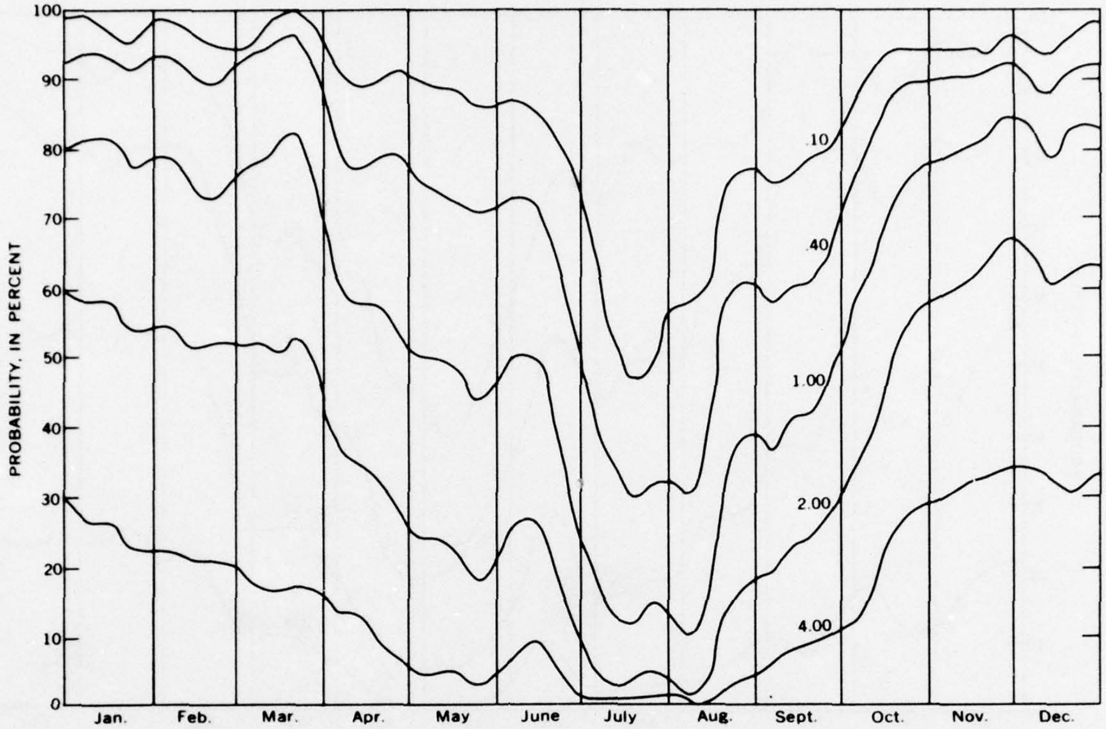


FIGURE 10.—Probability of various amounts of precipitation (inches) in 7 days at Cedar Lake (based on 1931-60 data).

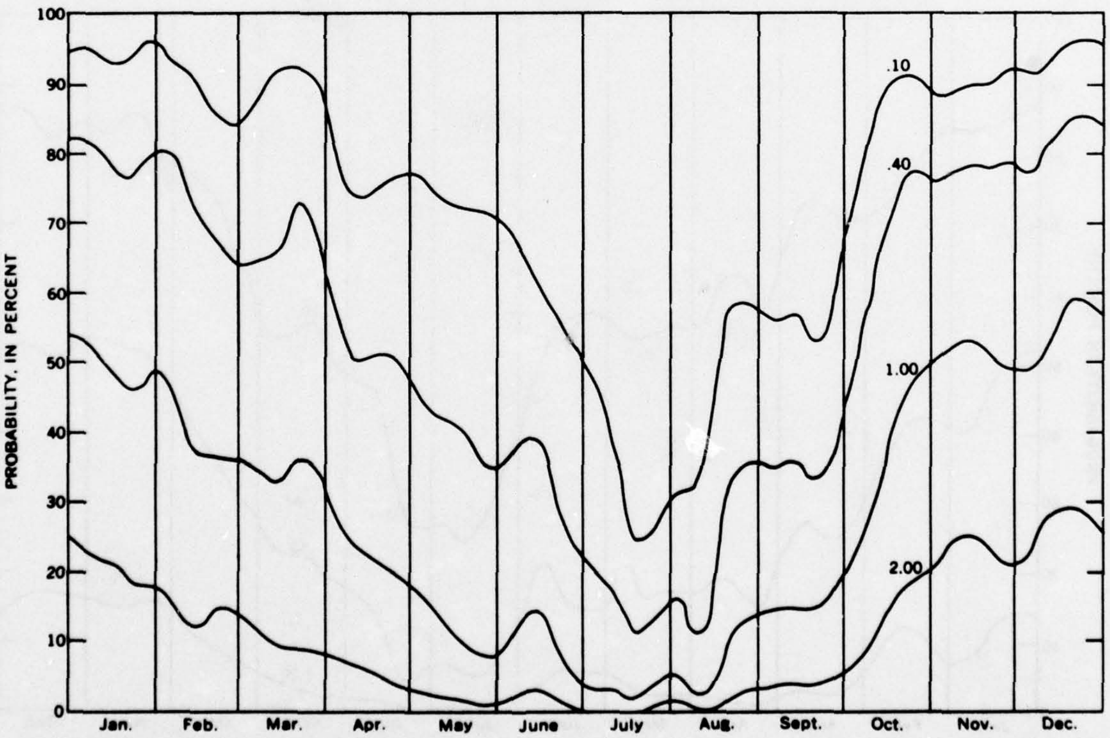


FIGURE 11.—Probability of various amounts of precipitation (inches) in 7 days at Puyallup Experiment station (based on 1931-60 data).

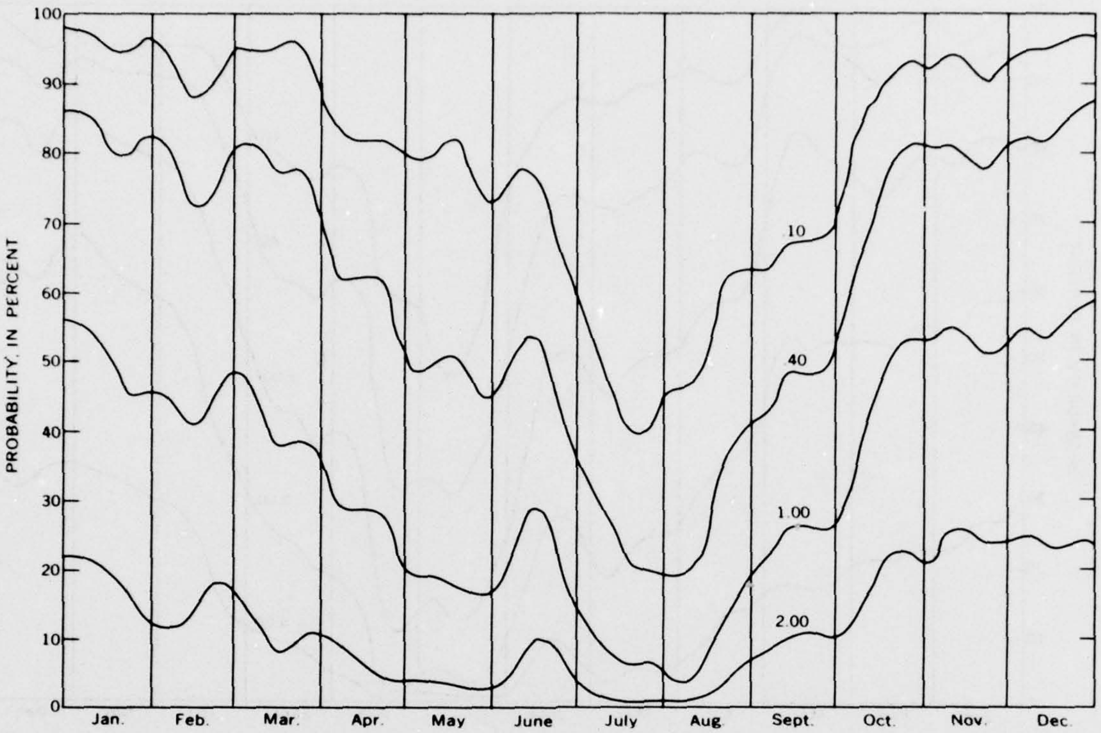


FIGURE 12.—Probability of various amounts of precipitation (inches) in 7 days at Sedro Woolley (based on 1931-60 data).

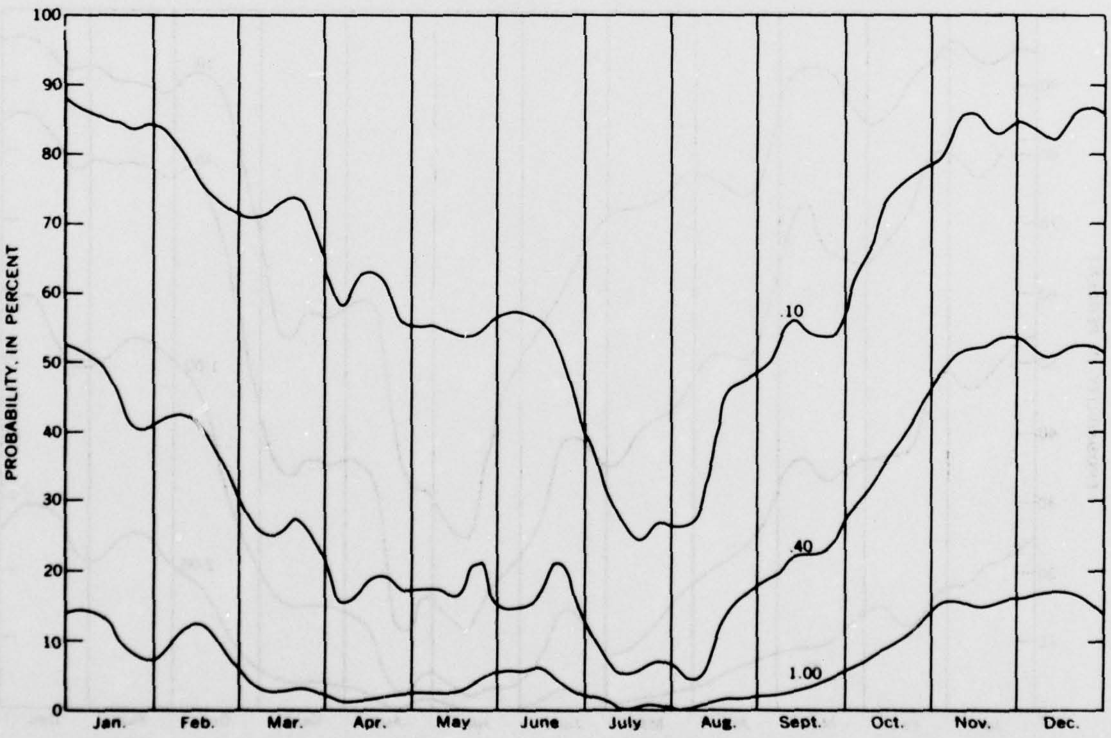


FIGURE 13.—Probability of various amounts of precipitation (inches) in 7 days at Sequim (based on 1931-60 data).

In the mountains, below-freezing temperatures are recorded on most nights between October and April. The coldest weather occurs when the Pacific Northwest is under the influence of continental, rather than maritime, air masses. Outbreaks of cold air through the Fraser River Canyon are observed each winter. Frequently, the cold air travels across the lowland in northern counties, then westward through the Strait of Juan de Fuca; however, during the more intense surges, it may spread over the entire Puget Sound Area.

Heating degree-days are units used by engineers in estimating heating requirements of dwellings, factories, and office buildings. A degree-day is a one-degree departure of the daily mean temperature per day, below a base of 65°F. Thus, a mean temperature of 55°F for 2 days represents 20 degree-days. The heating degree-days for an average year total about 5,000 in the lowlands, and increase to 8,000 or more at the summit of the Cascades (Table 7).

TABLE 7.—Average monthly and annual heating degree days, (base 65°F, at selected weather stations)

Area/Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
PUGET SOUND LOWLANDS													
Port Angeles	818	692	694	534	403	279	195	195	267	462	639	744	5922
Olga 2SE	818	680	660	492	363	240	174	164	249	437	624	738	5639
Sedro Woolley	837	672	629	447	298	174	105	96	198	409	630	763	5258
Seattle-Tacoma AP	828	678	657	474	310	173	74	81	186	406	633	750	5251
Shelton	825	678	651	459	288	156	62	62	165	406	633	756	5141
CASCADE & OLYMPIC FOOTHILLS													
Buckley 1NE	843	689	657	480	322	189	87	90	204	440	654	766	5421
Darrington R.S.	964	762	698	474	310	180	84	78	171	431	711	877	5740
Skykomish R.S.	1025	850	750	475	330	180	80	80	180	435	755	800	5860
WEST SLOPE CASCADES													
Diablo Dam	1025	825	780	535	325	175	50	50	170	475	765	925	6100
Greenwater	1055	845	840	635	445	295	150	185	305	575	835	985	7150
Longmire R.S.	1076	902	905	687	481	312	130	152	273	539	816	980	7253
SUMMIT CASCADES													
Mt. Baker	1180	990	1020	880	670	520	340	260	470	700	910	1120	9060
Paradise R.S.	1180	1030	1100	890	730	560	350	370	510	760	940	1140	9560
Snoqualmie Pass	1200	1010	950	730	580	410	220	240	370	650	940	1120	8420

The longest frost free period, 180 to 220 days, is on the San Juan Islands and elsewhere near the Sound. The shortest, 145 to 175 days, is in valleys separated from the Sound by ridges, and in the foothills. The average date of the last freezing temperature in the spring is mid-April near the Sound and mid-May or later in the colder valleys. The average date of the first freezing temperature in the fall occurs late in October near the Sound and the last of September in colder valleys (Table 8).

TABLE 8.—Dates in the spring and fall when freezing temperatures have a 10-percent and a 90-percent chance of occurrence

Station	Spring		Fall		Mean length of growing season (days)
	10-percent chance	90-percent chance	10-percent chance	90-percent chance	
PUGET SOUND LOWLANDS					
Clearbrook	May 31	Apr. 10	Sept. 7	Oct. 23	148
Olga 2SE	Apr. 14	Feb. 23	Oct. 20	Dec. 5	237
Olympia AP	May 29	Apr. 14	Sept. 20	Nov. 3	160
Puyallup Exp. Sta.	May 25	Apr. 3	Sept. 18	Nov. 3	165
Seattle-Tacoma AP	May 4	Mar. 15	Oct. 10	Nov. 25	207
Sedro Woolley	May 9	Mar. 18	Sept. 30	Nov. 15	193
Sequim	May 19	Mar. 28	Oct. 4	Nov. 19	187
Buckley 1NE	May 12	Mar. 23	Oct. 2	Nov. 17	192
Darrington R.S.	May 29	Apr. 17	Sept. 17	Nov. 2	151
Snoqualmie Falls	Jun 1	Apr. 11	Sept. 16	Nov. 1	156

Growing degree-days, sometimes referred to as heat units above a certain base temperature, are measures used to estimate the development of plants. Growing degree-days are defined as the difference between the daily mean temperature and the base temperature. The most frequently used bases are 40°F and 50°F. The average number of growing degree-days for each month from March through October, given in Table 9, were computed from average monthly temperatures at selected stations.

TABLE 9. — Average number of growing degree days above bases of 40° and 50°F, at selected weather stations

Area/Station	Mar 40°	Mar 50°	Apr 40°	Apr 50°	May 40°	May 50°	Jun 40°	Jun 50°	Jul 40°	Jul 50°	Aug 40°	Aug 50°	Sep 40°	Sep 50°	Oct 40°	Oct 50°	Annual 40°	Annual 50°
PUGET SOUND LOWLANDS																		
Sequim	127		243	39	406	121	516	216	632	322	645	334	522	222	329	56	3420	1310
Olga 2SE	152	12	261	57	412	124	510	210	608	297	611	301	501	201	338	59	3393	1261
Sedro Woolley	177	9	303	78	477	183	579	279	698	288	691	381	552	252	366	87	3843	1557
Monroe 2WSW	177	15	309	75	493	195	606	306	747	437	732	422	576	276	378	90	4018	1816
Puyallup Exp. Sta.	174	15	300	84	481	189	594	294	735	425	716	406	564	264	369	93	3933	1770
Shelton	155	9	300	72	487	186	597	297	753	443	741	431	588	288	369	90	3990	1816
CASCADE & OLYMPIC FOOTHILLS																		
Buckley 1NE	155	19	276	60	453	171	561	261	716	406	701	391	549	249	335	87	3746	1644
Darrington R.S.	118		273	63	462	183	573	273	729	418	713	403	555	255	329	81	3752	1676
Snoqualmie Falls	148	25	276	72	450	164	558	258	713	403	694	384	531	231	332	76	3702	1613
WEST SLOPE CASCADES																		
Cedar Lake	74		198	33	363	109	468	171	642	332	626	316	501	201	307	59	3179	1221
Greenwater	59		162	21	332	93	453	153	626	316	605	295	447	159	211	25	2895	1062
Palmer 3SE	112		243	54	431	146	537	237	716	406	701	391	558	258	347	77	3645	1569
SUMMIT CASCADES																		
Snoqualmie Pass	22		90		205	28	336	66	552	242	533	223	381	105	149	6	2268	670
Stampede Pass	3		45		143	9	267	31	502	192	484	178	357	87	109		1910	497
Paradise R.S.					84		153		403	109	403	109	279	69	78		1400	287

In winter, the relative humidity generally ranges from 90% at night to 75% in the afternoon; in spring and fall it ranges from 85 to 60%; and in summer, from 85 to 50%. During the months of June through September, the wet-bulb temperature in the Seattle area exceeds 66°F only 1% of the time, 63°F 5% of the time and 61° F 10% of the time.

The depth of frost in the soil varies from winter to winter, and is influenced by vegetation, soil type, snow cover, and temperature. In average winter, frost reaches depths of 5 to 10 inches in lowland areas near the Sound. In northern counties, frost may penetrate 15 to 24 inches if the ground is bare during extended cold periods. However, the ground rarely freezes in areas of dense forest or under a mountain snowpack.

CLOUD COVER AND SOLAR RADIATION

The number of clear or only partly cloudy days each month is from 4 to 7 in winter, 10 to 15 in spring and fall, and 20 or more in summer. Sunshine occurs during approximately 20% of the daylight hours in winter, 40 to 50% in spring and fall, and 60 to 70% in summer.

The "rain shadow" area northeast of the Olympic Mountains receives slightly more sunshine and less cloudiness than other localities near the Sound; however, the difference is not proportional to the decrease in precipitation.

Average daily solar radiation, both direct and diffused, ranges from less than 75 langleys in winter to more than 500 in summer as shown in Figure 14.

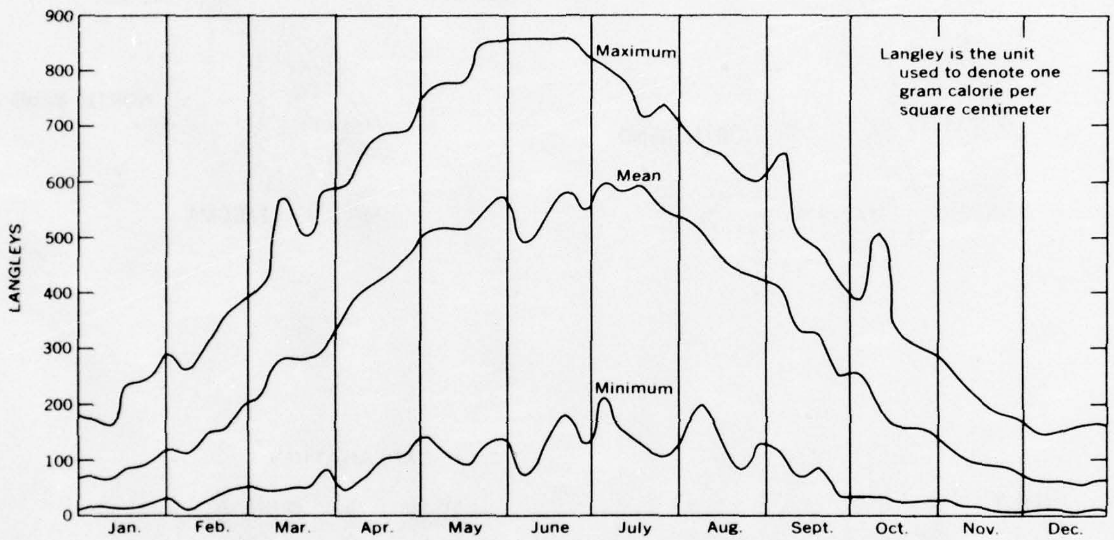


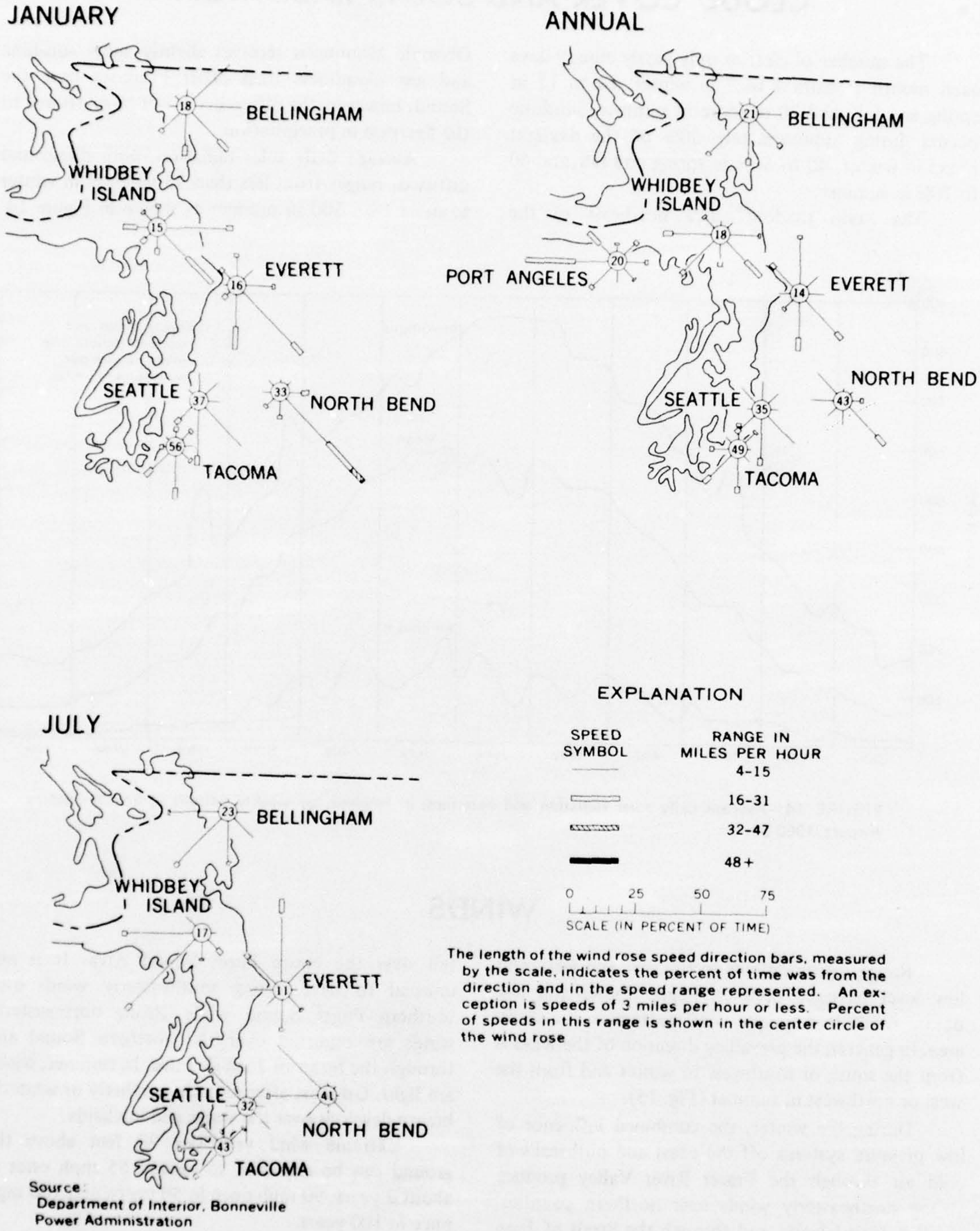
FIGURE 14.–Average daily solar radiation and extremes, in langleys, by weekly periods at Seattle-Tacoma Airport, 1950-59.

WINDS

Ranges of mountains to the east and west, and low level passages between Puget Sound and the ocean, result in a unique wind pattern in the study area. In general, the prevailing direction of the wind is from the south or southwest in winter and from the west or northwest in summer (Fig. 15).

During the winter, the combined influence of low pressure systems off the coast and outbreaks of cold air through the Fraser River Valley produce strong northeasterly winds over northern counties, the San Juan Islands, and through the Strait of Juan de Fuca. Occasionally, the northeasterly winds are felt over the entire Puget Sound Area. It is not unusual to have strong southeasterly winds over southern Puget Sound while strong northeasterly winds are reported over the northern Sound and through the Strait of Juan de Fuca. In summer, winds are light. On most afternoons, a northerly or westerly breeze develops over the water and lowlands.

Extreme wind velocities 30 feet above the ground can be expected to exceed 55 mph once in about 2 years, 90 mph once in 50 years, and 100 mph once in 100 years.



The length of the wind rose speed direction bars, measured by the scale, indicates the percent of time was from the direction and in the speed range represented. An exception is speeds of 3 miles per hour or less. Percent of speeds in this range is shown in the center circle of the wind rose

Source: Department of Interior, Bonneville Power Administration

FIGURE 15.–Surface wind roses for selected stations in the Puget Sound Study Area.

EVAPORATION AND EVAPOTRANSPIRATION

Water transferred to the atmosphere is the sum of water lost by evaporation from water surfaces and by evapotranspiration from land areas.

Annual gross evaporation from a Class-A pan is estimated at 25 to 35 inches. In an average season, monthly amounts increase from 3 inches in April to 6.5 inches in July, then decrease to 3.5 inches in September (Fig. 16). Annual evaporation of water from lakes and reservoirs is estimated to be 20 to 25 inches.

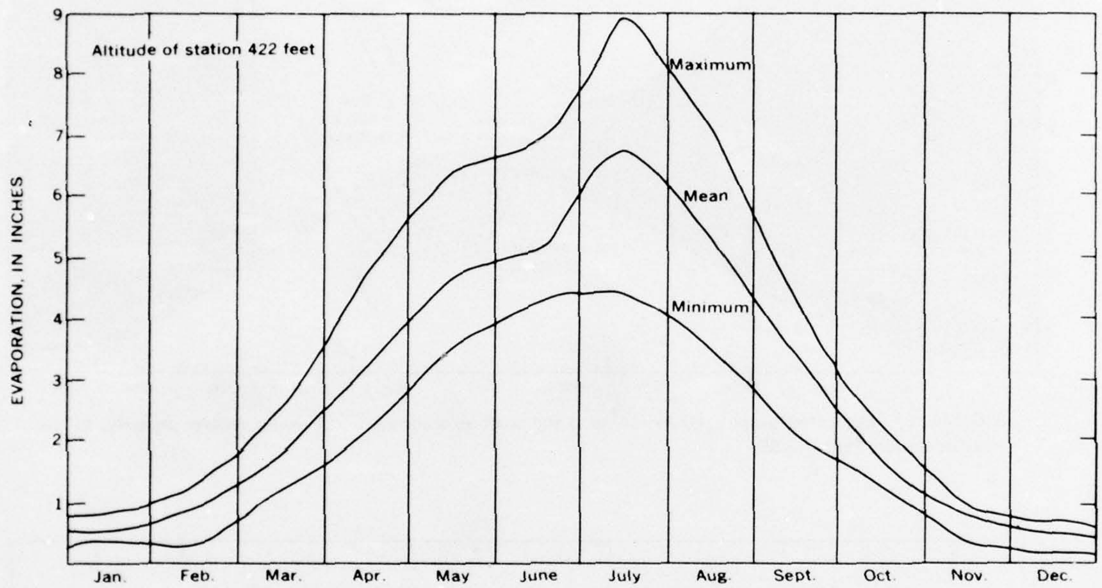


FIGURE 16.–Monthly class-A pan evaporation, in inches, at Seattle Maple Leaf Reservoir, 1941-60.

The term evapotranspiration refers to the total loss of water from soil as a result of evaporation from the soil and transpiration from growing plants. The amount of water transpired by plants depends on such factors as type of plant, moisture supply, and temperature. In areas not under irrigation, the amount of moisture available to plants depends upon the distribution of rainfall and the water-storage capacity of soils within the root zone.

Potential evapotranspiration is defined as the maximum amount of water which, if available, could be removed from the soil by the combined processes of evaporation and transpiration under conditions of average temperature. The term "actual evapotranspiration" is defined as the computed amount of water lost under existing conditions of temperature and precipitation. A comparision of the actual and potential evapotranspiration provides an estimate of the additional moisture that plants could use if a moisture deficit did not exist at any time. Techniques developed by Palmer and Havens for the application of Thornthwaite's method (1948) were used to compute evapotranspiration at the Palmer 3SE, Puyallup Experiment Station, Sequim, and Snoqualmie Falls stations. (Fig. 17-20).

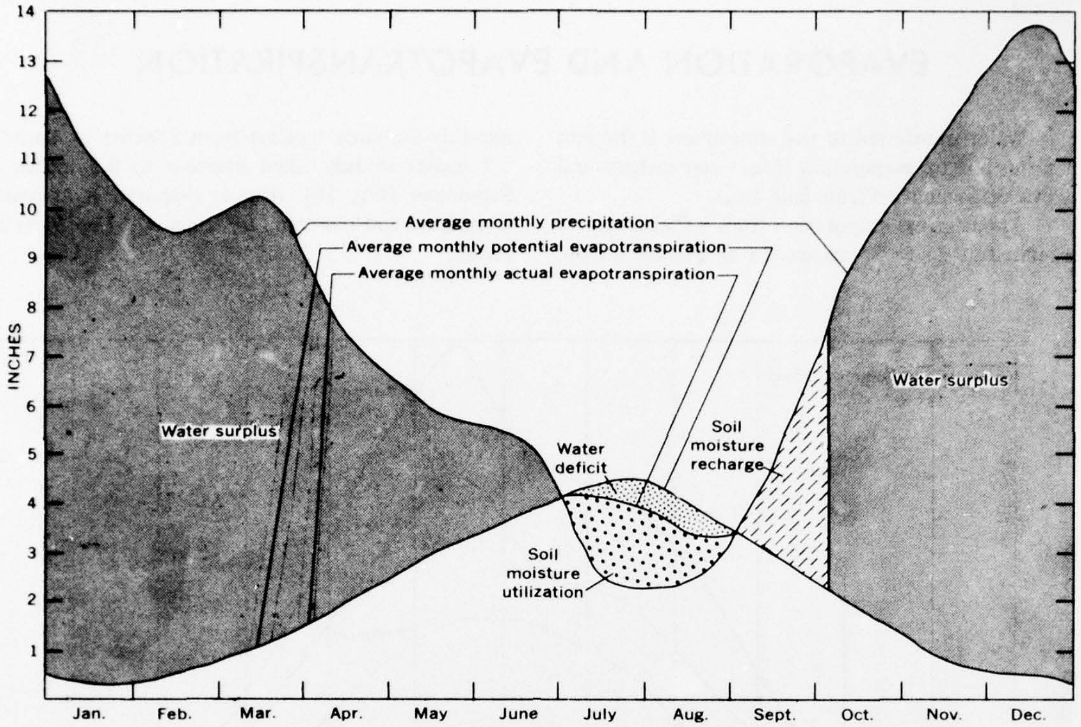


FIGURE 17.—Estimated evapotranspiration of a soil with an assumed 6-inch water storate capacity, at the weather station, Palmer 3 SE.

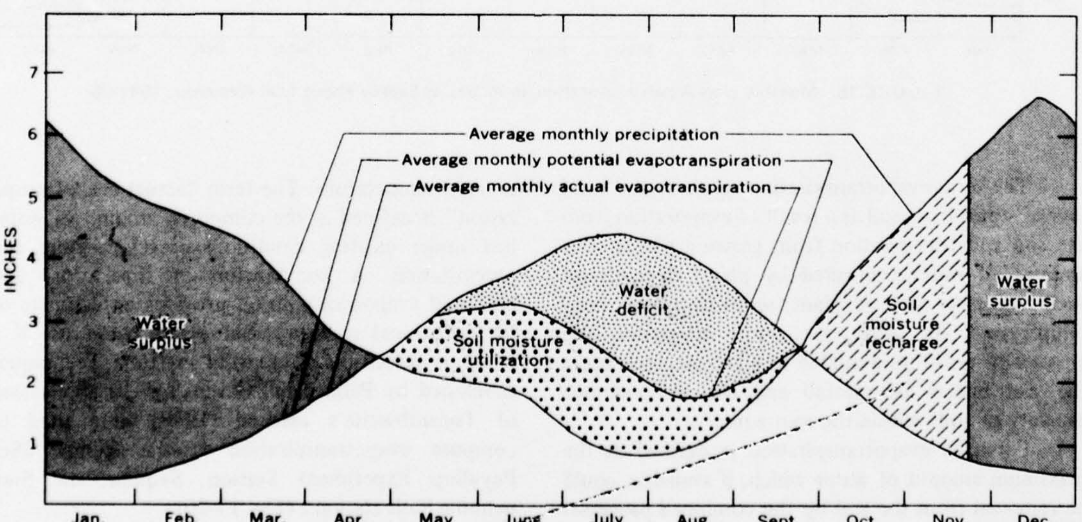


FIGURE 18.—Estimated evapotranspiration of a soil with an assumed 6-inch water-storage capacity, at the Puyallup Experiment Station.

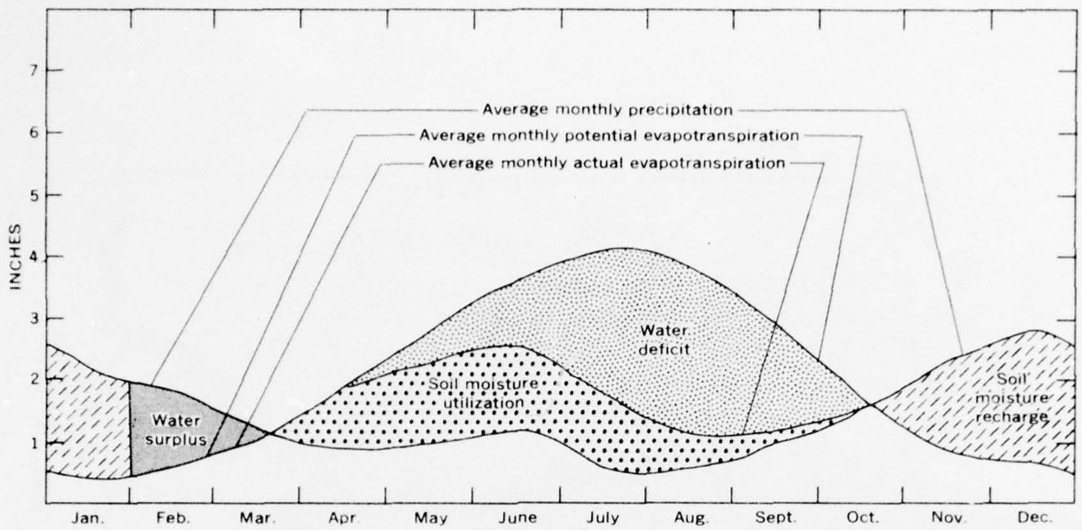


FIGURE 19.—Estimated evapotranspiration of a soil with an assumed 6-inch water-storage capacity, at Sequim.

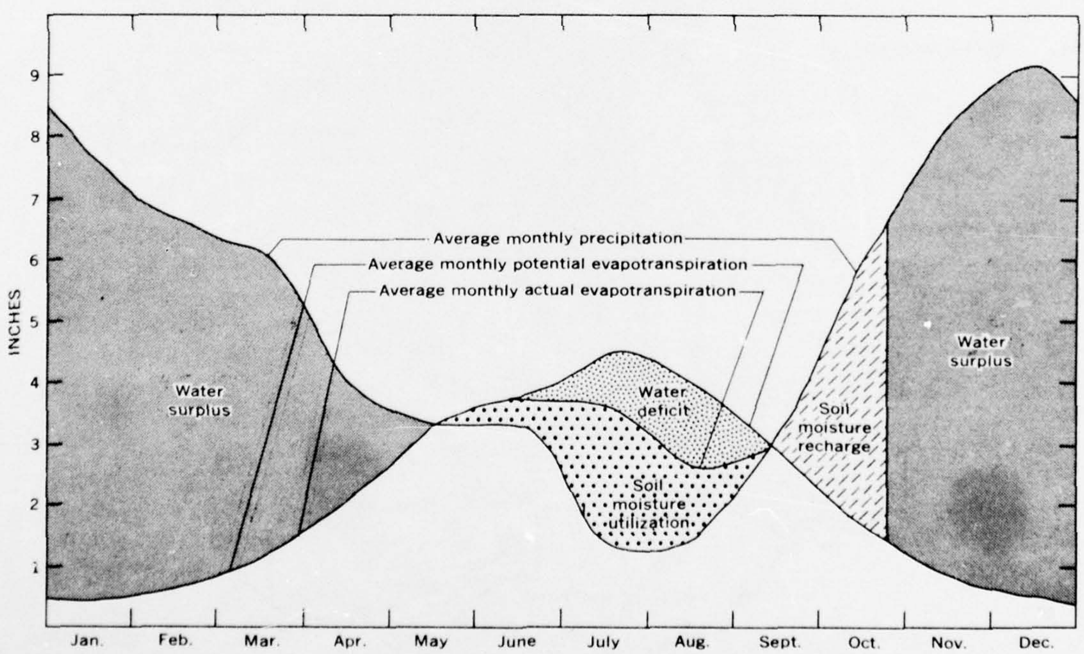


FIGURE 20.—Estimated evapotranspiration of a soil with an assumed 6-inch water-storage capacity, at Snoqualmie Falls.

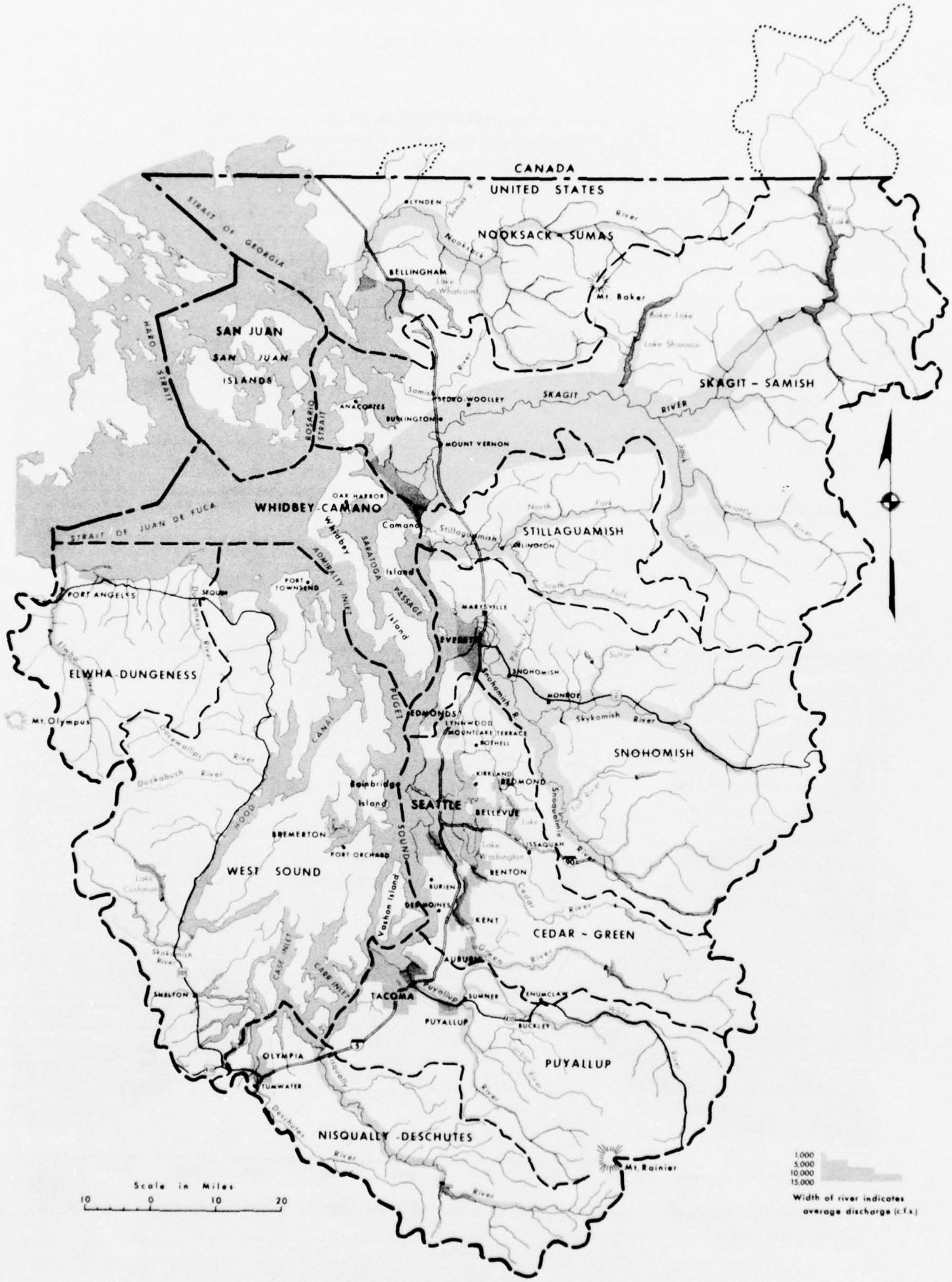


Figure 21. Average discharges of principal rivers

Hydrology of the Area

HYDROLOGY OF THE AREA

GENERAL DESCRIPTION

A measure of the water resources of the Puget Sound Area is provided by average runoff of all the rivers. Figure 21 shows the relative magnitude of the average discharge of the larger streams in the Puget Sound Area. Although some subsurface flow leaves the basins and is not measured as runoff, such flow is relatively insignificant for large watersheds. Surface runoff, therefore, is a fairly accurate measure of the total water supply, including water that is released from natural storage within the basin. It represents, in the hydrologic cycle, the total basin-wide precipitation minus losses by evapotranspiration and consumptive use.

In the Puget Sound Area, the total runoff during 1931-60, averaged about 39 million acre-feet per year. This is an impressively large volume of water; if all the land area of the region were suddenly inundated with such a volume at a uniform depth, the resulting lake would be 55 inches deep. There are few places in the United States where the average annual runoff is so great; the average runoff for the conterminous states is less than 10 inches. In the State of Washington, surface-water runoff averages about 26 inches per year, representing a volume of 95 million acre-feet. Thus, 41% of the State's total runoff is produced in the Puget Sound Area.

In spite of the large total supply in the Area, water may not be available where and when it is needed to meet existing and future needs. Average annual runoff ranges from less than 15 inches in some of the northern lowlands to as much as 140 inches in a few mountain areas. In Table 10, the estimated average runoff is listed for each of 11 basins in the Puget Sound Area. For most basins these estimates are based on observed discharges plus synthesized runoff from small ungaged areas.

Table 10 shows the rather large difference in average depth and volume of runoff in the basins. Nearly half of the total runoff in the region is contributed by the Skagit and Snohomish Basins.

In addition to the large areal variations in runoff, even larger variations occur with time. These will be discussed in more detail by basins in later sections of this report. The seasonal fluctuations result in periods of flooding and extreme low flow; thus water problems occur in spite of the abundant overall water supply. Studies of the frequency of floods and low flows are essential, therefore, in water management planning to lessen the impact of such variations in flow.

FLOODS

The river basins in the Puget Sound Area are characterized by narrow mountain valleys with steep gradients and broad river valleys in the lowlands. Most of the agricultural and urban development has occurred in the lowlands, where flood plains are subject to frequent and damaging floods.

Major floods in the region occur, almost without exception, as a result of warm rainstorms during the months of October through March. Though the floodwaters are primarily from rain, they are often augmented by melted snow, especially if the snow mantle prior to the rainfall extended to low altitudes. Snowmelt floods in the spring and summer usually are not severe and do little damage. In contrast, rain-runoff peaks in the region are characterized by high magnitudes for periods ranging from a few hours on small streams to several days on the larger rivers. The frequency and magnitude of floods in the basins are described in more detail in later sections.

TABLE 10.—Estimated average runoff in the Puget Sound Area

Basins	Drainage area (sq mi)	Average annual runoff, 1931-60 Inches	(Acre-ft)
Nooksack-Sumas	1,262	55	3,700,000
Skagit-Samish	3.025	71	[1]11,500,000
Stillaguamish	690	80	2,940,000
Snohomish	1,900	70	7,090,000
Cedar-Green	1,151	36	2,210,000
Puyallup	1,217	41	2,660,000
Nisqually-Deschutes	1,016	36	1,950,000
West Sound	2,018	46	4,950,000
Elwha-Dungeness	690	45	1,660,000
Whidbey-Camano	209	[2]10	[2]111,000
San Juan	176	[2]10	[2]94,000
Total or average	13,355	55	38,865,000

[1] Does not include inflow from Canada.
[2] Entirely estimated.

The method of flood-frequency analysis in the Puget Sound Study is in accordance with procedures developed by the U.S. Corps of Engineers (Beard, 1962). Analyzed streamflow data include not only the annual peak discharges at a gaging station, but also the highest average discharge for periods of 1 day, 3 days, and other time intervals in each water year. The result is a series of curves that show the probability of a particular maximum discharge being exceeded.

LOW FLOWS

One of the most critical factors concerning water resources planning and development in the Puget Sound Area is the occurrence of minimum streamflows. The frequency of low flows affects the use of surface water for nearly every conceivable purpose. It is essential, therefore, that a low flow frequency analysis be considered as part of the planning for any proposed water use.

Minimum streamflows in most of the region occur between July and November. The magnitude and duration of low flows are influenced considerably by surface and ground water storage. In high altitude watersheds, melt water from glaciers and snowfields sustains summer flows, and the minimum discharge of many mountain streams occurs during the winter. In low-lying stream basins, however, storage may be nearly depleted during dry summer months, and streamflows then become critically low at a time when water is most needed for many uses.

A measure of low flow often used in hydrologic studies is the minimum average discharge for periods of various length in the climatic year. (The climatic year is from April 1 to March 31.) The variability of these annual minimum discharges, and their probability of occurrence, are shown by lowflow frequency curves. Such curves have been prepared for many gaging sites in the Puget Sound Area, and are used in a later section of this report to describe the frequency of low flows in each of the basins.

A measure of the low-flow yield of a stream is the minimum 7-day average discharge, at two year recurrence intervals, in cubic feet per second per square mile of drainage area. This value, called the "low flow index" in this report, has been determined for the base period 1946–64 at many stream-gaging sites in the study area. The low-flow index makes possible a quick appraisal of the normal low-flow yield of streams having different size drainage areas. The low-flow indexes have been classified as shown in the following table:

Low Flow Class	Range in low-flow index (cfs per square mile)
Poor	Less than 0.50
Fair	0.51–1.00
Good	1.01–1.50
Excellent	More than 1.50

Using these classifications, areal variations in the low-flow indexes are shown in Figure 22. The figure indicates that yields generally are greatest in the mountainous areas where average runoff is high and storage is provided by snow and ice. Poor low-flow yields in contrast, are characteristic of lower altitude streams that receive only small amounts of ground-water inflow.

A second value computed for each of the stream-gaging stations in this study was the slope of the minimum 7-day frequency curve, which is a measure of the year-to-year variability of low flows. The slope index is the ratio of the minimum 7-day average discharges at two-year and twenty-year recurrence intervals. Variations in the slope of frequency curves at different sites are due to differences in basin characteristics. A low value of the slope index means that year-to-year differences in low flow normally are small. A high index indicates a steep slope, and large variations in low flow. The slope indexes in the study area range from 1.16 to 8.33, most are less than 2.0.

The third value derived from the low-flow frequency curves is the spacing index. The spacing, or spread, between the minimum 7-day and 183-day frequency curves is indexed by the ratio of the discharges at the two-year recurrence interval on both curves. The spacing between the curves for different durations of low-flow is influenced by the same basin characteristics that affect the slope. If the basin is relatively impermeable, the frequency curves are widely spaced. In contrast, curves for a stream draining permeable materials are more closely spaced. The spacing ratios computed for gaging stations in the study area range from a minimum of 1.30 for Huge Creek, on the Kitsap Peninsula, to a maximum of 22.2 for Pilchuck Creek, a tributary to Stillaguamish River. In general, the spacing indexes are less than 5.00.

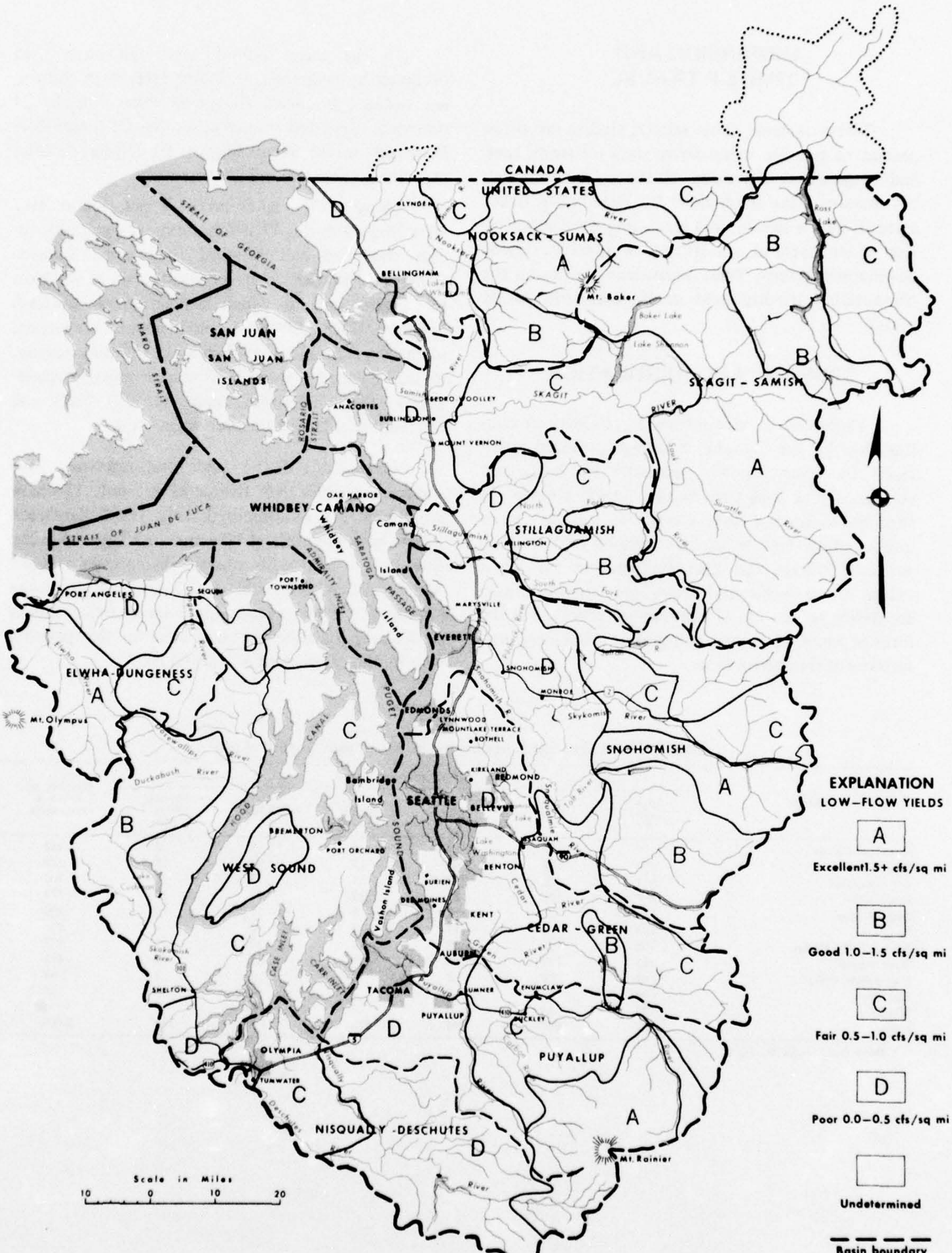


Figure 22. Areal variation of low-flow yields of streams

DISPERSION AND TIME OF TRAVEL

Where streams carry wastes, studies are often needed to provide quantitative data on travel time and longitudinal dispersion of the pollutants. Such information often is obtained by introducing tracer material into a stream, and measuring the concentration of the tracer at, and its time of travel to, various downstream points. These measurements permit the computation of dispersion coefficients (Fischer, in press).

STORAGE AND REGULATION

Variations in streamflow are influenced considerably by the amount of storage provided artificially by reservoirs, and naturally by lakes and glaciers. On a long-term basis, natural storage (in addition to ground water) tends to maintain more uniform flow and to shorten periods of low flow. Artificial storage can maintain uniform flow, and reduce flood peaks and times of minimum flow, depending on the use of the reservoir. Storage in the form of snow, of course, is important, but only on a seasonal or short-term basis.

In the Puget Sound Area, the water area occupied by reservoirs, including lakes with controlled outlets, is about 70 square miles. In all, 24 reservoirs are listed in this appendix. Of these, Ross Reservoir, in the Skagit Basin is the largest; its total capacity is about 1.4 million acre-feet.

Many of the lakes in the Puget Sound Area were formed during Pleistocene time, by glacial scour that deepened and widened pre-existing troughs. Some are "kettles" that represent casts of remnant ice blocks around which deposition of outwash occurred. Over 2,800 lakes and reservoirs are located in the Puget Sound Area (Table 11) and they occupy, in the aggregate, about 175 square miles (Walcott, 1965). The Snohomish Basin has 771 lakes and reservoirs; the largest number in the Area.

Over half of the lakes and reservoirs have surface areas less than five acres and only 116 have areas greater than a hundred acres. The Cedar-Green Basins have the greatest lake area—52.7 square miles. The largest lake with uncontrolled outlet is Lake Sammamish with an area of 7.7 square miles. Lake Washington is much larger—34.5 square miles—but its outlet is artificially controlled, a feature that places it outside the category of a "natural lake".

TABLE 11.—Lakes and reservoirs in the Puget Sound Area[1]

Basin	Surface area, in acres						Number of lakes & reservoirs
	Less than 5	5-15	15-30	30-50	50-100	Greater than 100	
Nooksack-Sumas	89	33	9	8	1	5	145
Skagit-Samish	289	108	48	15	22	18	450
Stillaguamish	111	33	10	9	3	3	169
Snohomish	417	196	74	33	24	27	771
Cedar-Green	124	43	21	8	11	15	222
Puyallup	153	41	21	6	3	4	228
Nisqually-Deschutes	101	56	19	11	10	20	217
West Sound	221	119	51	11	17	19	438
Elwha-Dungeness	48	14	4	0	0	2	68
San Juan	26	10	3	1	4	2	46
Whidbey	28	14	6	1	4	1	54
Total	1,557	667	266	103	99	116	2,808

[1] Data from Walcott, 1965

Glaciers are an integral part of the water resources of the study area. About 116 square miles of the Puget Sound Area—representing about two-thirds of the glacier area in the State of Washington—is covered by glaciers. The Skagit Basin has the most glaciers and the largest total area of glacial ice. Table 12 shows the number and area of glaciers by basins.

TABLE 12.—Distribution and area of glaciers as of 1965 by basins

Basins	Area of glacier ice (sq mi)	Number of glaciers
Nooksack-Sumas	16.6	63
Skagit-Samish	63.3	233
Stillaguamish	.6	6
Snohomish	2.2	16
Cedar-Green	0	0
Puyallup	24.7	25
Nisqually-Deschutes	6.4	8
West Sound	.6	10
Elwha-Dungeness	2.0	25
Whidbey-Camano	0	0
San Juan	0	0
Total	116.4	386

Almost all the glaciers occur at altitudes where precipitation exceeds 100 inches, and they produce each year an average of about 9,000 acre-feet of streamflow per square mile of glacier. The total amount of water stored in the study area as glacier ice is estimated to be about 13 million acre-feet.

These frozen reservoirs have several unique characteristics that are pertinent to the water resources development of the region: (1) precipitation is stored in the winter and released during the summer, usually in July or August; (2) runoff from glaciers approximately equals precipitation when averaged over a long period of time, but in hot, dry years runoff can greatly exceed total precipitation and in cool, wet years an appreciable amount of precipitation is stored; (3) evaporation, transpiration, and other losses from glaciers is small; and (4) glacier rivers may transport large sediment loads.

DIVERSIONS

With few exceptions, the largest diversions in the Puget Sound Area are for municipal supplies and major industrial plants. In some area diversions for agriculture are important. Water is diverted for hydroelectric power generation and to operate fish hatcheries and forest-products mills, and plants in many places. In most places where water is diverted from a stream for power generation, the water is returned to the stream a hundred feet downstream from the point of diversion. The extent to which water is diverted from streams in each of the basins will be discussed later in this appendix.

SURFACE-WATER QUALITY AND FLUVIAL SEDIMENT

Surface water in the study area is a calcium-bicarbonate type, of low dissolved solid content, and of excellent quality for most uses. Dissolved solids content in most streams usually is less than 75 ppm (parts per million), and in some streams it may be less than 20 ppm at times. Hardness of water also is very low, generally less than 60 ppm.

The low degree of mineralization and the chemical composition of water in the streams is attributed to the nature of the soils and rocks in the watersheds: abundant precipitation and runoff in much of the region have extracted a large part of the soluble material.

The sanitary quality of water in streams, as indicated by a test that determines the most probable number (MPN) of coliform bacterial in a 100-milliliter sample, is good in many reaches. MPN values usually are less than 100, except in populated areas where the MPN is much higher, often more than 1,000, and in some streams it has been known to exceed 24,000.

The temperature of a stream can be as important as other aspects of its quality and its rate of flow. Stream temperatures are affected by many influences of the stream's environment. Some of these influences are properties of the natural setting, whereas others are associated with man-made alterations in the drainage basin.

In 1944, the U.S. Geological Survey began recording water temperature at the time of visits to most stream-gaging stations. These periodic readings, designated as spot observations, are spaced several weeks apart and are taken mostly during daylight hours. In 1951, that agency began to install thermographs on streams so that short-term fluctuations in temperature could be detected, chiefly for fisheries use. The thermograph record, because it is continuous, can supply information on random changes in temperature that may be hydrologically significant.

Both types of record, the spot measurement and the continuous measurement are useful in detecting changes in stream regimen. For a long

period of record, spot observations will approximate average daytime temperatures. Since a stream's maximum temperature usually occurs during daylight hours, the long-term spot observations also approximate the stream's maximum temperature. Continuous thermograph records can also be used to extend the adequacy of spot observations.

Temperatures of streams in the study area are rather low throughout most of the year although values exceeding 75° F have been measured in many streams in the east side of Puget Sound during July and August. On the Olympic Peninsula, streams warmer than 70° F are rare.

In both urban and undeveloped areas, knowledge of the processes of erosion and sedimentation are important in optimizing the beneficial uses of water and land resources. In a region such as the Puget Sound Study Area, where heavy rainfall occurs, large volumes of rock and soil are eroded from higher altitudes and are transported to lower areas by large, swift streams.

The largest stream in the Study Area, the Skagit River, transports about 10 million tons of suspended sediment during an average year, which is at least five times the sediment load of any other stream in the Area. Most of the sediment is transported during periods of high runoff. During low flows many streams are clear, and have suspended sediment concentrations of 20 ppm or less. Streams fed by glacial melt water, however, are often turbid and sediment-laden, particularly in warm weather. The Nooksack, Skagit Puyallup, and Nisqually Rivers are streams of this type.

In upper watershed areas, where the terrain is mountainous and precipitation is abundant, the soils are shallow and stony. Heavy vegetative cover in these areas normally prevents excessive erosion. In lower drainage areas, where the terrain is formed largely on glacial drift, soils have varying depths and drainage characteristics. Sloughing of stream banks and significant movement of bed material occur in these areas during periods of high runoff. Where construction, logging operations or cultivation cause the land to be bare of vegetation in the winter months, sheet or rill erosion is commonplace during periods of prolonged rain. Erosion is discussed in greater detail in the Water Related Land Resources and Watershed Management Appendices.

EFFECTS OF URBANIZATION

One of the significant factors affecting surface-water runoff relates to man's increasing tendency to congregate in ever-expanding urban complexes. Although the urbanized area in most large watersheds is generally a small percentage of total basin area, the disruption in natural drainage patterns can be of major significance. Among the major effects of urbanization are sealing off ground-water recharge areas and accelerating storm-water runoff. In addition, as an area converts from field and forest to home and factory, water must be diverted from its natural channels to supply the needs of people and industry, and these waters are returned to the water course through artificial drainage conduits, carrying the waste products of industrial production and human living. Additional effects are associated with soil-disturbing construction activities, which give rise to both erosion and sedimentation problems. Some evidence even supports the contention that changes attendant to urbanization can significantly alter the local climatic regimen. In the following discussion an attempt will be made to place some of these problems in perspective.

In 1962, about 90 sewage-collection systems in the Puget Sound Area served a total of about 1.1 million people, or 75% of the regional population. The area encompassed by the sewered communities totaled some 305 square miles, or 3.6% of the land area of the Puget Sound Area. Although most of the region is mountainous woodland, and therefore, unsuitable for large metropolitan growth, the urban buildup proportionately exceeds that of the country as a whole (U.S. Public Health Service, 1963; U.S. Bureau of Census, 1963).

The amount of land given over to urban development varies appreciably from basin to basin. To show the amount of land that has been urbanized in comparison to that used for other purposes, Table 13 lists all the known land uses for the several basins. On the basis of data listed, urban buildup constitutes about 4.2% of the regional land area, ranging from less than 0.5% in the Stillaguamish Basin to nearly 25% in the Cedar-Green Basins.

Studies to quantitate the total impact of this urbanization in the Puget Sound Area have not as yet been undertaken; however, some work in other parts of the nation treats some of these effects. A long-term study was carried out on a 5.12-square-mile area of the Permanente Creek basin in Santa Clara County, California. As a result of the increase in impervious surface in the project area from about 4% of the total area in 1945 to 19% in 1958 to the ratio of outflow to total inflow increased from 1.18 to

TABLE 13.—Estimated distribution of land use, in acres in the Puget Sound Area

Basins	Total land and inland water (Sq. Mi.)	(acres)	Cropland	Range-land	Woodland	Rural nonfarm[1]	Urban built-up[2]	Inland water[3]
Nooksack-Sumas	1,256	804,000	137,000	12,000	609,000	13,000	21,000	12,000
Skagit-Samish	3,044	1,948,000	100,000	20,000	1,754,000	20,000	19,000	35,000
Stillaguamish	684	438,000	35,000	1,000	384,000	6,000	7,000	5,000
Snohomish	1,903	1,218,000	72,000	2,000	1,055,000	29,000	36,000	24,000
Cedar-Green	1,161	743,000	53,000	3,000	447,000	34,000	167,000	39,000
Puyallup	1,203	770,000	37,000	6,000	593,000	26,000	97,000	11,000
Nisqually-Deschutes	1,008	645,000	45,000	43,000	508,000	20,000	19,000	10,000
San Juan	177	113,000	19,000	9,000	72,000	9,000	3,000	1,000
Whidbey-Camano	209	134,000	23,000	2,000	85,000	12,000	11,000	1,000
West Sound	2,022	1,294,000	46,000	5,000	1,124,000	64,000	42,000	13,000
Elwha-Dungeness	700	448,000	24,000	2,000	409,000	5,000	6,000	2,000
TOTALS	13,367	8,555,000	591,000	105,000	7,040,000[4]	238,000	428,000	153,000

[1] Rural nonfarm; rural living, farmsteads, gravel pits.
[2] Urban built-up; densities in excess of 3 houses per 10 acres; roads, railroads, airports, etc.
[3] Inland water; lakes and reservoirs of measurable size and sizeable rivers.
[4] *721,000 acres open land associated with forest areas included in Woodland figure.*

1.70 (Harris and Rantz, 1964, p. 16).

A similar study conducted in the Washington, D.C. area showed that the net effect of decreased infiltration and runoff concentration time caused by urbanization in drainage areas larger than four square miles can increase the flood peaks of any recurrence interval by 180% (Carter, 1961, p. 9–11).

One of the most significant and potentially most damaging effects of storm-water runoff is sedimentation. The quantities of sediment from a large watershed can vary widely, depending upon precipitation, type of soil, slope, and land use. Studies conducted in the Potomac Basin have shown that the highest contributions, as much as 50,000 tons per square mile, originate in areas undergoing urban development, whereas the estimated average annual sediment discharge from the entire basin is only 170 tons per square mile (Wark and Keller 1963, p. 19–20).

In one of the most complete studies of urbanization, runoff from a 27-acre residential and light-commercial section of Cincinnati was measured and analyzed over a 2-year period. This area, which was served by separate storm sewers, had a population density of 9 persons per acre, was 37% paved, had an average slope of 2–3%, and a concentration time in the sewer of about 15 minutes. In terms of several constituents, the annual waste load in storm runoff, expressed as a percent of the total annual sewage loads were: suspended solids, 60%; chemical oxygen demand, 33%; biochemical oxygen demand, 7%; total phosphate, 5%; and total nitrogen, 14%. In terms of bacterial pollution, 10% of the coliform analyses exceeded 460,000 MPN and 90% exceeded 2,900 MPN. By way of comparison fresh domestic sewage normally contains about 100 million coliform bacteria per 100 ml in the summer.

Although, as stated earlier, no comprehensive studies have as yet been undertaken to evaluate quantitatively the many effects that urbanization has had upon the surface-water hydrology in all the Puget Sound Area, a number of limited investigations have been made. Most of the major metropolitan areas have sponsored studies by consulting engineers for the purpose of designing storm-sewer systems. Such studies were completed during the latter 1950's for the two largest cities of the Area, Seattle and Tacoma (Brown and Caldwell, 1957, 1958). In both of these studies, significant problems such as street and basement flooding, property damage, and nuisances were noted. Damage was reported to water uses such as swimming and bathing, and fish and wildlife. Both cities are now in the process of correcting the severest of these problems.

One of the primary reasons for the creation, in 1959, of the Municipality of Metropolitan Seattle (METRO) was to implement proposals for terminating the discharge into Lake Washington of waste discharges that were partly responsible for stimulating excessive algal growths and reducing the lake's value as a recreational resource. The diversion proposal involved complete separation of sanitary and storm sewers along the east shore, and installation of holding tanks to temporarily store excess storm-water flows in the combined west shore systems. Additional details on this program are given in the Water Quality Control Appendix.

A study of Green Lake in northern Seattle was instituted in 1957 by the University of Washington to assess the effects of urbanization on this intensively

used recreational water body (Sylvester and Anderson, 1964, p. 11–12). Use of the 256 acre lake was being hindered by algal blooms, bacterial pollution, aquatic plantgrowths, mud deposits, and outbreaks of swimmers' itch. Following a two year intensive investigation of the environmental factors contributing to the accelerated eutrophication of the lake, a program to retard the aging process was undertaken: (1) dredging and shoreline improvement to increase water circulation, (2) exclusion of storm water to deter shoaling and decrease nutrient contributions, (3) addition of 10 million gallons per day of low nutrient city water to hasten flushing, and removal of littoral vegetation. Subsequent observations show that use of city water for flushing has resulted in significant decrease in algal population, and a consequent improvement in the lake's aesthetic quality (Oglesby, 1966).

The Soil Conservation Service of the U.S. Department of Agriculture has investigated and projected the effects of urbanization on a 26 square mile area near Kent, in the Cedar-Green Basins (written commu., 1967). This area, with a 1960 population of 14,100, is expected to experience rapid growth to over 80,000 people by 2020. The watershed in 1960 was primarily rural, consisting of cutover forests, orchards and farmsteads. Under ultimate urbanization an estimated 50% of the ground surface will be paved and much of the remainder will have been compacted to the point of greatly reducing the water intake capacity of the soil.

Based on studies of a 2.4 square mile subwatershed, the time of concentration of storm runoff is expected to be greatly reduced, peak flows will be nearly doubled, and duration of runoff and minimum flows will be greatly reduced. Expanding these data to the 26-square-mile study area, momentary maximum flood flow increases in 2020 are expected to range from 135 to 165% of present values, for floods with recurrence intervals of 100 years and two years, respectively.

GROUND WATER

Most of the ground water supplies in the study area are contained in unconsolidated sedimentary deposits of Quaternary age. As shown in Figure 2, the deposits occupy most of the lowlands and the mountain-valley extensions of many principal streams.

For the purposes of this regional study, the Quaternary sedimentary deposits are grouped into four categories:

1. alluvium, associated with postglacial streams;
2. recessional outwash, associated with the most recent (Fraser) glaciation;
3. till, associated with the Fraser Glaciation; and
4. sediments deposited prior to the till.

The fourth group includes not only advance outwash of the Fraser Glaciation, but also deposits associated with earlier glacial and interglacial periods. Formal stratigraphic names that have been applied to many sedimentary units in localized areas are not used in this study because regional correlations are as yet uncertain. Moreover, in stream valleys, recessional outwash and recent alluvium are difficult to discriminate in some places because of the gradual transition from glacial to postglacial conditions.

Aquifers having the most favorable water-bearing properties occur in recessional outwash, alluvium, and gravel and sand of deposits older than the till. These aquifers usually contain fresh water at depths as much as a few hundred feet below sea level, except in near-shore areas, where aquifers less than 200 feet deep may contain sea water. In some localized areas near shorelines (for example, near Tacoma, Shelton, Bremerton, and Sequim), fresh water may occur at great depths–as much as 1,500 feet below sea level.

The aquifers that contain fresh water receive most of their recharge from infiltration of precipitation, principally during winter months. Areas most conducive to recharge are those of gentle slope formed on recessional outwash and alluvium. Smaller but nevertheless significant amounts of water infiltrate the till deposits to recharge underlying aquifers.

Much of the ground water discharge is through springs and seepage areas along streams. However, considerable quantities of discharge are through springs along shorelines and below the level of tidewater. Although large amounts of water are dischaged through wells, the mangitude is quite small in comparison to the natural discharge.

The recharge-discharge relationship described above applies mainly to the shallow water table aquifers. The response of these aquifers to recharge associated with seasonal precipitation is reflected by corresponding seasonal changes of 5 feet or more in water level. The deeper aquifers, which generally are confined under artesian pressure, receive recharge in

their unconfined, upgradient parts, from the overlying shallower aquifers by seepage through intervening sediments of rather low permeability. Seasonal water level fluctuations in the deeper aquifers are generally less than two feet which suggests less response to variations in precipitation that occurs in the shallower aquifers.

Water levels in shallow and deep aquifers generally are less than 100 feet below land surface, and in many places are less than 50 feet below. In aquifers beneath high till-capped uplands, however, water levels are commonly deeper—in some places as much as 450 feet or more. Where deeper aquifers continue beneath low-altitude areas adjacent to the uplands, artesian pressures in these aquifers are often sufficient to provide flowing-well conditions in the lower areas.

Water-level declines owing to pumping generally are not significant under present conditions of ground-water development. Slight declines have occurred in Tacoma's well field. Large water-level declines have occurred in a localized area northeast of Renton, but only in aquifers of pre-Quaternary age.

A desirable feature of much of the ground water in the study area is its satisfactory chemical quality and uniformly low temperature. Dissolved solids content is generally less than 200 ppm and values of hardness are normally less than 120 ppm. Ground-water temperatures are characteristically close to 50 F. Iron content is objectionable in a few areas, particularly in water from shallow aquifers. High iron content (above 0.3 ppm) has been reported for well waters from deeper aquifers in some places. However, this high iron content may not everywhere be representative of the deeper zones, but may instead be the result of well construction that allows iron-bearing water to enter the well from shallow zones. In some areas near shorelines, ground water is highly mineralized owing to the encroachment of sea water into fresh water zones as a consequence of pumping. An indication of potential sea-water encroachment into fresh-water zones may be provided by high concentrations of chloride. In general, chloride concentrations are less than 10 ppm, but are somewhat greater in areas underlain by Tertiary rocks containing saline waters.

Opportunities for obtaining ground water are more favorable south of Seattle, where zones of water bearing coarse sand and gravel in both recessional outwash and subtill strata are relatively abundant in comparison to northern areas. In the areas south of Seattle, ground water is used for municipal, irrigation, and industrial purposes to a greater degree than in northern areas.

Figure 23 shows generalized well yields that may be expected in the Puget Sound Study Area. The areas of different well yield are based largely on yields of existing wells. However, the complex distribution and variable properties of Quaternary deposits in the Puget Sound Area preclude accurate prediction of favorable aquifers; hence, well yields could be obtained locally that are either much greater or much less than is shown by the map. Moreover, the amount of ground water that can be produced beneficially at a particular locality depends on additional factors such as well spacing, thoroughness of well construction and completion, and potential deterioration of water quality. On a regional and long-term basis, however, the total ground-water discharge, both natural and artificial, cannot exceed the total recharge.

Additional water could be introduced into the aquifers in some areas where the ground-water body is made up of coarse materials to land surface. The water introduced either through wells or by means of settling basins is called artificial recharge. Such recharge is desirable—or is hydraulically possible—only when the water table in the aquifer has been drawn down significantly by pumping. In some valleys, declines in level caused by pumping would automatically induce added recharge from streams, a feature that would minimize the need for artificial recharge but would decrease streamflow, perhaps to the detriment of downstream users.

In this study, availability of ground water in the lowlands of each basin except San Juan is based on estimates of natural recharge to aquifers by infiltration of precipitation. The estimates are based on precipitation and streamflow data for small undeveloped watersheds containing various geologic units. Assuming that long-term recharge is equivalent to the long-term discharge of ground water, a reasonable measure of recharge is provided by areal factors developed from records of those streams whose low flows are derived, largely from ground-water discharge. In addition, the assumption is made that evapotranspiration losses are satisfied mainly from water in the soil and to a minor extent from water in the ground-water body. On this basis the average annual recharge to aquifers in the lowlands of the study area is conservatively estimated as 800,000 acre-feet.

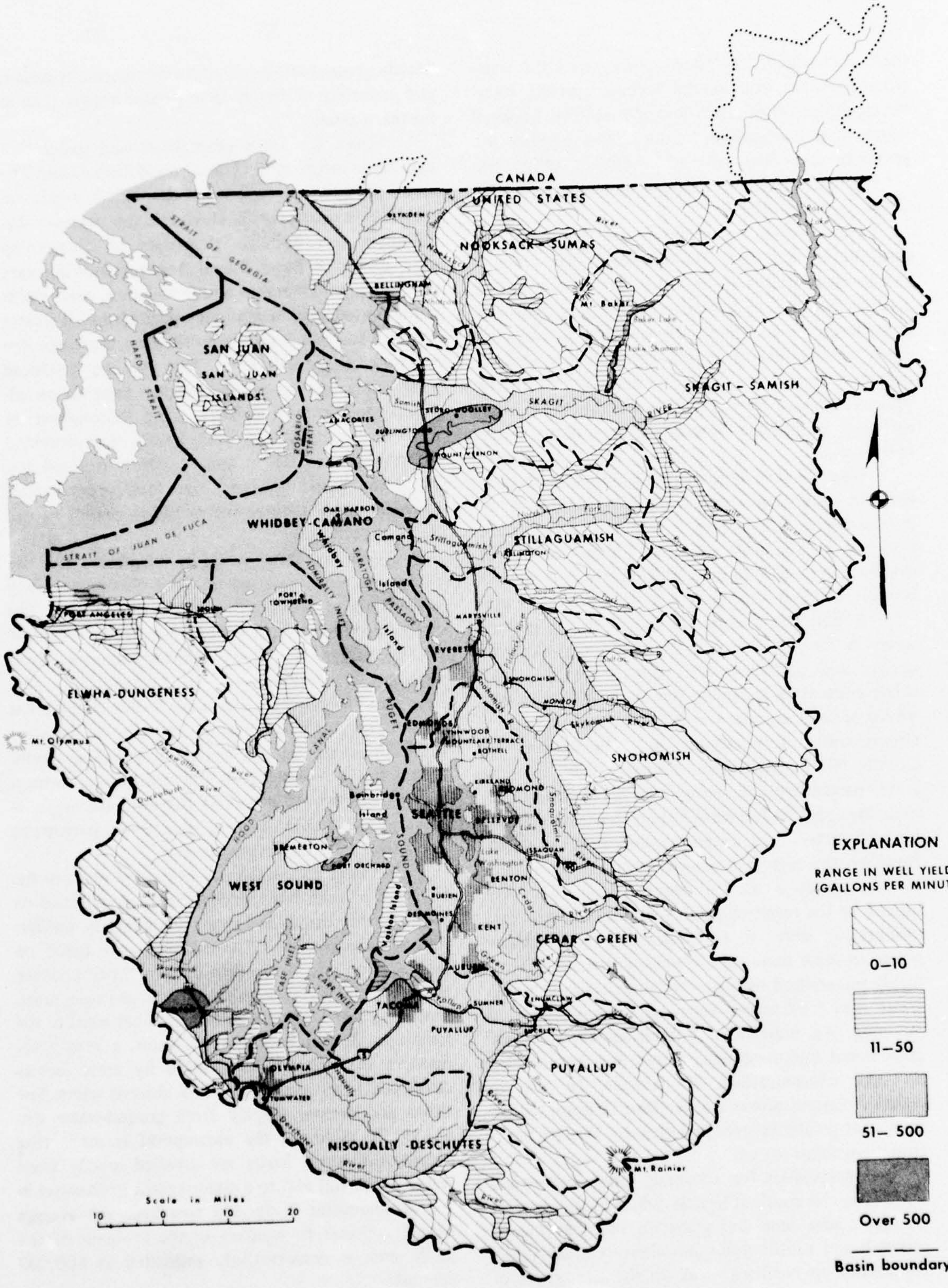


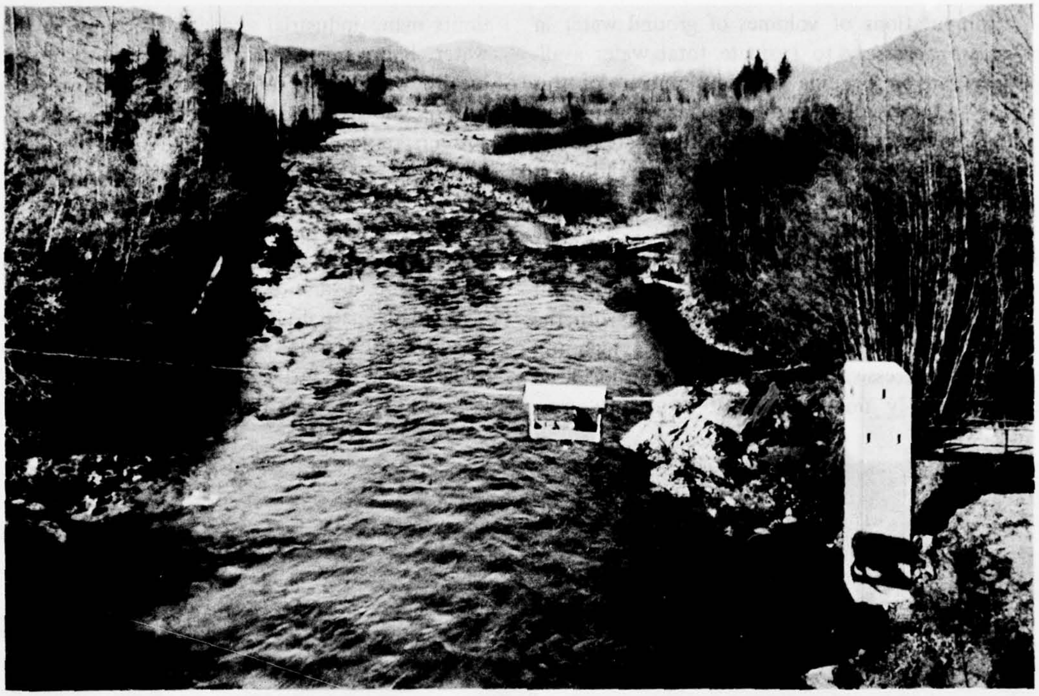
FIGURE 23. Generalized yields of wells in Puget Sound Study Area.

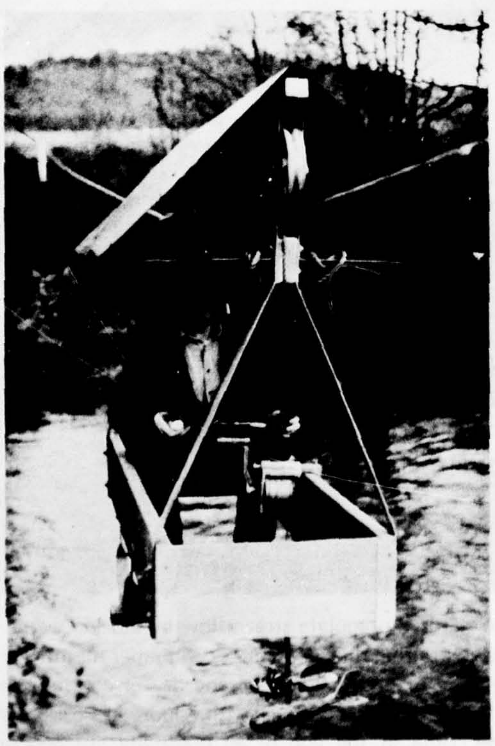
Computations of volumes of ground water in storage are necessary to evaluate total water availability in an area, guide the development of this resource and govern its use, even in areas of abundant recharge; however, because of an unfortunate lack of data the computation of a value for ground-water storage was not possible.

Although a large volume of water is available for development in the Puget Sound Area as a whole, certain problems may become critical as development of large ground-water supplies keeps pace with the expected increase in demand. For example, high iron content and excessive hardness of water in localized areas and highly mineralized water in some areas limits many industrial and domestic uses of ground water. Salt-water encroachment, now detected only locally, could occur as a result of excessive pumping in shoreline areas. Bacterial contamination of shallow aquifers could become a problem in the more densely populated areas where individual household water supplies are from shallow wells and sewage disposal is through septic tanks. The improper location or operation of refuse-disposal facilities could also cause serious ground-water contamination.

Inadequate drainage is presently a hindrance to development of some areas. In areas where the water table is near the surface, improper irrigation and land use could result in further drainage problems.

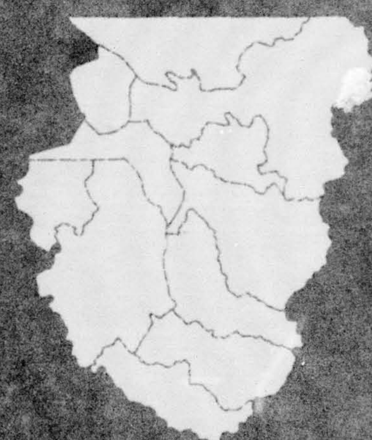
About 740 glaciers in the North Cascade Range help to naturally regulate streamflow by storing water at times of high precipitation, releasing large amounts of water during the warm and dry summer months, and compensating by changes in natural storage for the effects of unusually warm and dry or cool and wet years. Typical of these glaciers is McAllister Creek Glacier, as shown above, with Eldorado Peak in the background. This photograph was taken in September 1958 at the end of an unusually hot and dry summer. Photograph by Austin Post.





STREAM GAUGING STATION. Stream discharges are measured by a current meter suspended from a cable car. Automatic recording water level gauge on shore is calibrated to measured discharges.

Hydrology of the Basins



HYDROLOGY OF THE BASINS

NOOKSACK—SUMAS BASINS
SURFACE WATER

The Nooksack-Sumas Basins comprise 1,628 square miles, including 1,256 square miles of land and inland water (Fig. 33). The largest and most important stream in the basins, the Nooksack River, drains 826 square miles, of which 49 square miles are in Canada. The river's major tributaries head in the Mount Baker-Shuksan area of the North Cascades and converge near the town of Deming. From Deming the river meanders through 37 miles of braided channel in the lowlands to its outlet in Bellingham Bay where, from 1931 to 1960, it discharged an average of about 2,750,000 acre-feet annually.

Between the Nooksack Basin and the Canadian border lie the headwaters of the Sumas and Chilliwack Rivers, which flow northward to the Fraser River in British Columbia. The Chilliwack River heads on the north slopes of the Pickett Range, and drains 174 square miles in Washington. The average annual runoff in this area is estimated to be about 70 inches, which means that the average volume of runoff in the upper Chilliwack Basin is about 650,000 acre-feet per year. The Sumas River drains some of the lowlands in the western part of the basins, where the average annual runoff is only about 20 inches. The average volume of runoff in the Sumas River basin in Washington is estimated at about 74,000 acre-feet per year.

Practically all the surface-water storage in the basins is contained in natural lakes, Lake Whatcom being the largest, and in snowfields and glaciers on Mount Baker and Mount Shuksan. The Nooksack River contains water of excellent quality except for the occurrence of fine-grained suspended sediments derived from melting glaciers.

STREAMFLOW

Runoff Characteristics

The eastern uplands of the Nooksack-Sumas Basins, including the high alpine areas of Mount Baker and Mount Shuksan, present a sizable orographic barrier to the flow of moisture-laden maritime air and annual runoff exceeds 140 inches in the vicinity of the higher peaks. In contrast, runoff averages less than 15 inches in some of the lowland areas near the coast. For the entire area, the average annual runoff is about 55 inches, equivalent to a volume of 3,700,000 acre-feet.

Three major forks drain the mountainous part of the Nooksack River basin. The North Fork, as it is known locally, is actually the main stem of the Nooksack River. It is joined by the Middle and South Forks near the town of Deming. Streamflow data from the North and South Forks indicate that unit runoff from both these watersheds averages about 7.2 cfs per square mile. Fragmentary records of the Middle Fork suggest that unit runoff in that watershed is about the same or slightly greater. In general, the total average contribution of the three forks is about 2,400,000 acre-feet per year. Nearly one-half of this total is from the North Fork watershed, about one-third is from the South Fork, and about one-sixth from the Middle Fork. Tributary contributions in the lowlands increase the average annual runoff of the Nooksack River by about 300,000 acre-feet.

The annual runoff record for the Nooksack River at Deming for the period 1936–63 is shown in Figure 24. The highest discharge (131% of 30 year average, 1931–60) occurred in 1954 and the lowest (67%) in 1944.

The seasonal pattern of runoff from high-altitude areas in the Nooksack-Sumas Basins is represented in Figure 25. Reasonably high flows result from the direct runoff of autumn rains, but with the advent of colder winter temperatures, the runoff normally declines as increasing amounts of winter precipitation are stored as snow on the mountain slopes. The gradual decline continues during the winter months until streamflow reaches a minimum level in about March. Thereafter, snowmelt begins with rising temperatures, and runoff rapidly increases, reaching a maximum usually in June. A snowmelt-runoff recession follows during July and August, but summer flows are maintained at fairly high levels by the release of glacial melt water.

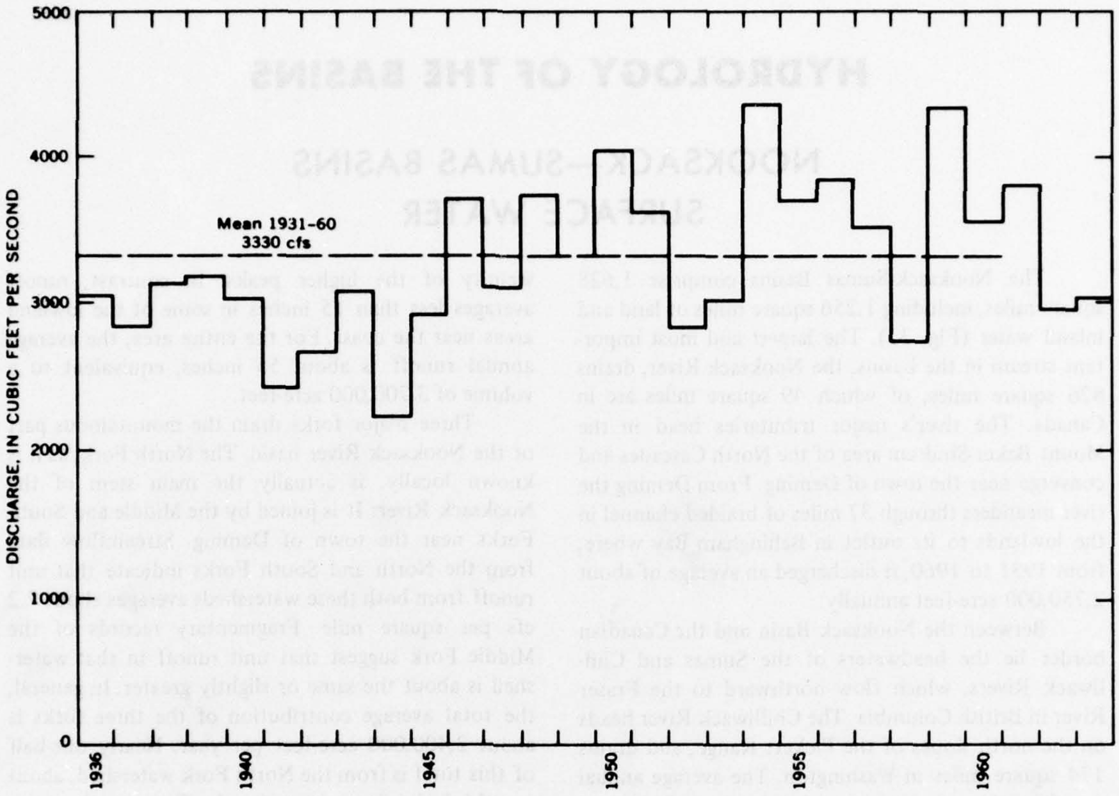


FIGURE 24.—Annual discharges, Nooksack River at Deming.

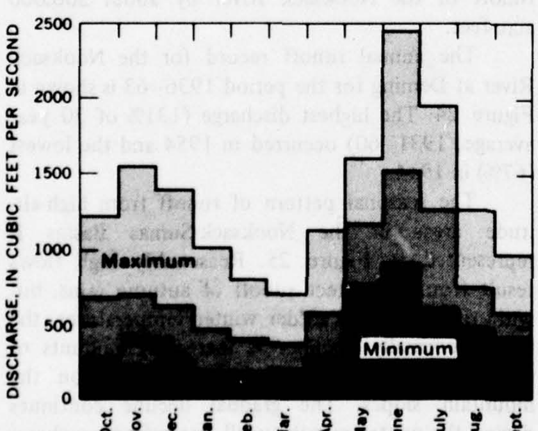


FIGURE 25.—Maximum, mean and minimum monthly discharges, Nooksack River below Cascade Creek near Glacier, 1931-60.

The seasonal pattern of runoff for the South Fork Nooksack River near Wickersham and on the Nooksack River at Deming is represented in Figures 26 and 27. In the South Fork watershed, winter temperatures are milder than in the North Fork basin, so that direct runoff from winter rain is greater and snowpack accumulation is less. Long-term average monthly discharges of the South Fork are about the same in winter and in spring, but the winter flows are more variable. Because no glacial melt water supports summer streamflows, discharges often become quite low during August.

Small streams that drain the Nooksack lowlands generally have an extended high-flow period resulting from rains during the fall, winter, and spring. The higher flows recede in late spring, and lowest discharges usually occur in August or September. The summer low flows of these streams are supported entirely by ground-water contributions.

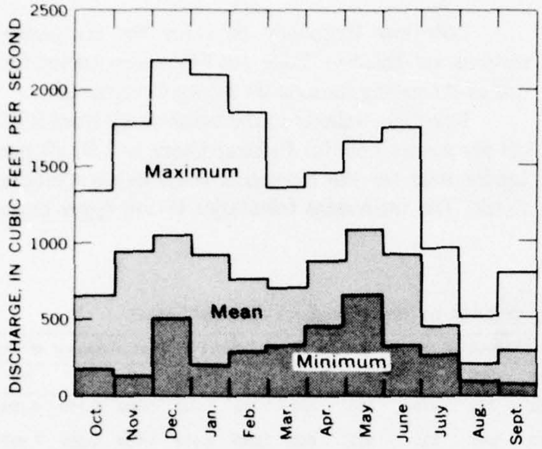


FIGURE 26.—Maximum, mean and minimum monthly discharges, South Fork Nooksack River near Wickersham, 1931-60.

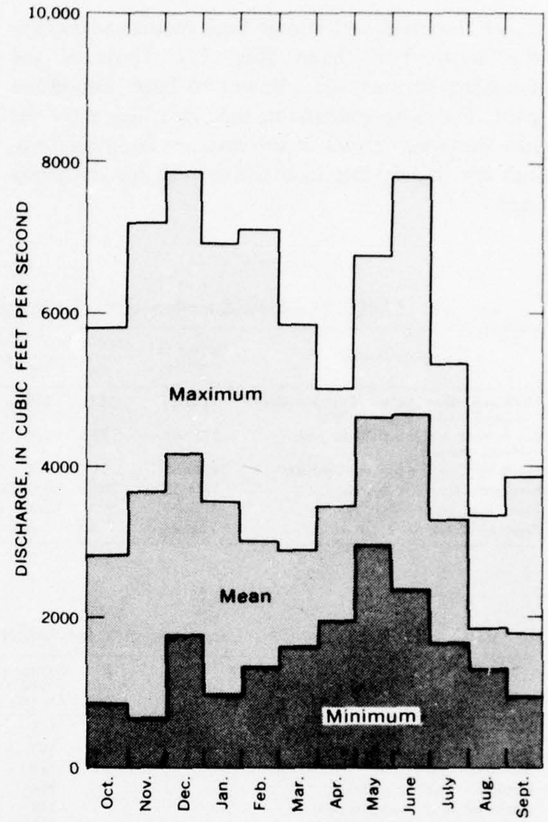


FIGURE 27.—Maximum, mean and minimum monthly discharges, Nooksack River at Deming, 1931-60.

The stream gage on the Nooksack River at Deming measures runoff from over 70% of the Nooksack River basin. Streamflow at this site follows the seasonal pattern described for the North and South Forks. The base flow is about 1,800 cfs in the summer; it increases during the fall and winter as the level of the ground-water reservoir recovers. The winter flow is characterized by a series of sharp rises, with the highest peak usually occurring in December. Runoff generally decreases from December through March, then increases again as a result of snowmelt and reaches a daily flow of about 5,700 cfs by the middle of June.

The variability of daily stream flow in the Nooksack-Sumas Basins is presented as flow-duration data for selected gaging stations in Table 14.

Flood Characteristics

Floods caused by rain with accompanying snowmelt produce characteristically sharp rises, followed by recession that are almost as rapid. Two or more flood peaks often occur within two weeks. Flood damage results when the discharge at Deming is 20,000 cfs or more, and flows of this magnitude seldom last longer than 72 hours. The maximum discharge recorded at the Deming site, 43,200 cfs, occurred on February 10, 1951.

Flood-frequency curves for the Nooksack River at Deming are presented in Figure 28. The record at the Deming gage started in 1935, but frequency statistics were extended to the period 1927-64 by correlation with the much longer record, for South Fork Skykomish River near Index.

The ability of a stream to transport water at high discharge rates without causing damage depends on its channel characteristics. An understanding of these features is provided by a graphical representation of the stream's water-surface profile for various rates of discharge. Water-surface profiles of the Nooksack River from mile 0 to mile 37 are shown on Figure 29. Profiles for the lower 14-mile reach of the South Fork are shown on Figure 30. Discharge rates and average velocities are designated at various points on the profiles.

Low-Flow Characteristics

Low-flow characteristics of streams in the Nooksack-Sumas Basins are compared using indexes from low-flow frequency curves at six gaging stations (Table 15). The low-flow indexes are excellent in the

upper Nooksack and Middle Fork basins and good in the South Fork basin (Fig. 22). Those of the low-lying streams and adjacent to Puget Sound are poor. The slope and spacing indexes which show the low flows for stream in this area are fairly uniform, and are slightly less than the average for the study area.

Low-flow frequency data for the six gaging stations are listed in Table 16. Frequency curves for one of the gaging stations are shown in Figure 31.

Low-flow indexes in the basins range from 0.22 cfs per square mile for Fishtrap Creek to 1.90 cfs per square mile for the Nooksack River below Cascade Creek. The main-stem tributaries in the upper basin

TABLE 14.—Flow-duration data for gaging stations in the Nooksack-Sumas Basins

Gaging station	Period of analysis	Flow in cubic feet per second, which was equaled or exceeded for indicated percent of time											
		99	95	90	80	70	50	30	20	10	5	1	0.1
Nooksack River below Cascade Creek near Glacier	1938-65	155	210	258	335	410	590	880	1,120	1,500	1,880	2,750	4,400
South Fork Nooksack River near Wickersham	1935-65	82	108	140	240	335	540	840	1,060	1,450	1,900	3,500	7,400
Skookum Creek near Wickersham	1949-65	21	29	38	53	68	104	155	195	265	340	560	1,050
Nooksack River at Deming	1936-57	700	1,010	1,220	1,540	1,850	2,650	3,750	4,550	6,000	7,400	11,500	23,000
Nooksack River near Lynden	1946-65	920	1,250	1,470	1,840	2,200	3,080	4,200	5,100	6,600	8,200	14,000	29,000
Fishtrap Creek at Lynden	1949-65	2.8	4.6	5.9	8.2	11.5	25	42	57	85	118	218	400

TABLE 15.—Low-flow characteristics for selected gaging stations in the Nooksack-Sumas Basins

Gaging station	Drainage area (sq mi)	Low flow index	Slope index	Spacing index
Nooksack River below Cascade Creek near Glacier	105	1.90	1.69	2.85
South Fork Nooksack River near Wickersham	103	1.16	1.67	4.54
Skookum Creek near Wickersham	23.1	1.19	1.89	3.53
Nooksack River at Deming	584	.81	1.59	2.55
Nooksack River near Lynden	648	1.79	1.75	2.50
Fishtrap Creek at Lynden	22.3	.22	1.92	2.40

TABLE 16.—Low-flow frequency data for selected gaging stations in the Nooksack-Sumas Basins
[Discharge adjusted to base period April 1, 1946, to March 31, 1964]

Gaging station	Number of consecutive days	Stream flow in cfs, for indicated recurrence intervals, in years						
		1.05	1.30	2.0	5	10	20	30
Nooksack River below Cascade Creek near Glacier	7	330	255	200	148	130	118	110
	30	440	310	235	173	150	130	120
	90	660	480	370	270	238	210	200
	183	860	690	570	450	390	350	330
South Fork Nooksack River near Wickersham	7	190	150	119	91	79	71	66
	30	280	200	152	110	92	80	74
	90	600	400	275	170	138	120	112
	183	850	680	540	380	310	250	225
Skookum Creek near Wickersham	7	45	35	27.5	20	17	14.5	13.5
	30	58	45	36	26	21.5	18.5	17
	90	93	72	56	39	32	27	25
	183	144	119	97	72	60	50	45
Nooksack River at Deming	7	1,420	1,220	1,060	860	760	670	620
	30	2,000	1,600	1,340	1,070	950	850	800
	90	3,050	2,400	2,000	1,600	1,400	1,260	1,200
	183	3,850	3,200	2,700	2,150	1,850	1,600	1,500
Nooksack River near Lynden	7	1,630	1,380	1,160	900	760	660	610
	30	2,070	1,680	1,400	1,110	1,000	880	830
	90	3,200	2,550	2,100	1,600	1,400	1,200	1,100
	183	4,200	3,450	2,900	2,250	1,900	1,700	1,600
Fishtrap Creek at Lynden	7	7.8	6.2	5.0	3.7	3.1	2.6	2.4
	30	9.6	7.2	5.7	4.1	3.4	2.9	2.6
	90	12.5	8.9	6.9	5.0	4.0	3.3	2.9
	183	21	16	12	8.4	6.7	5.4	4.8

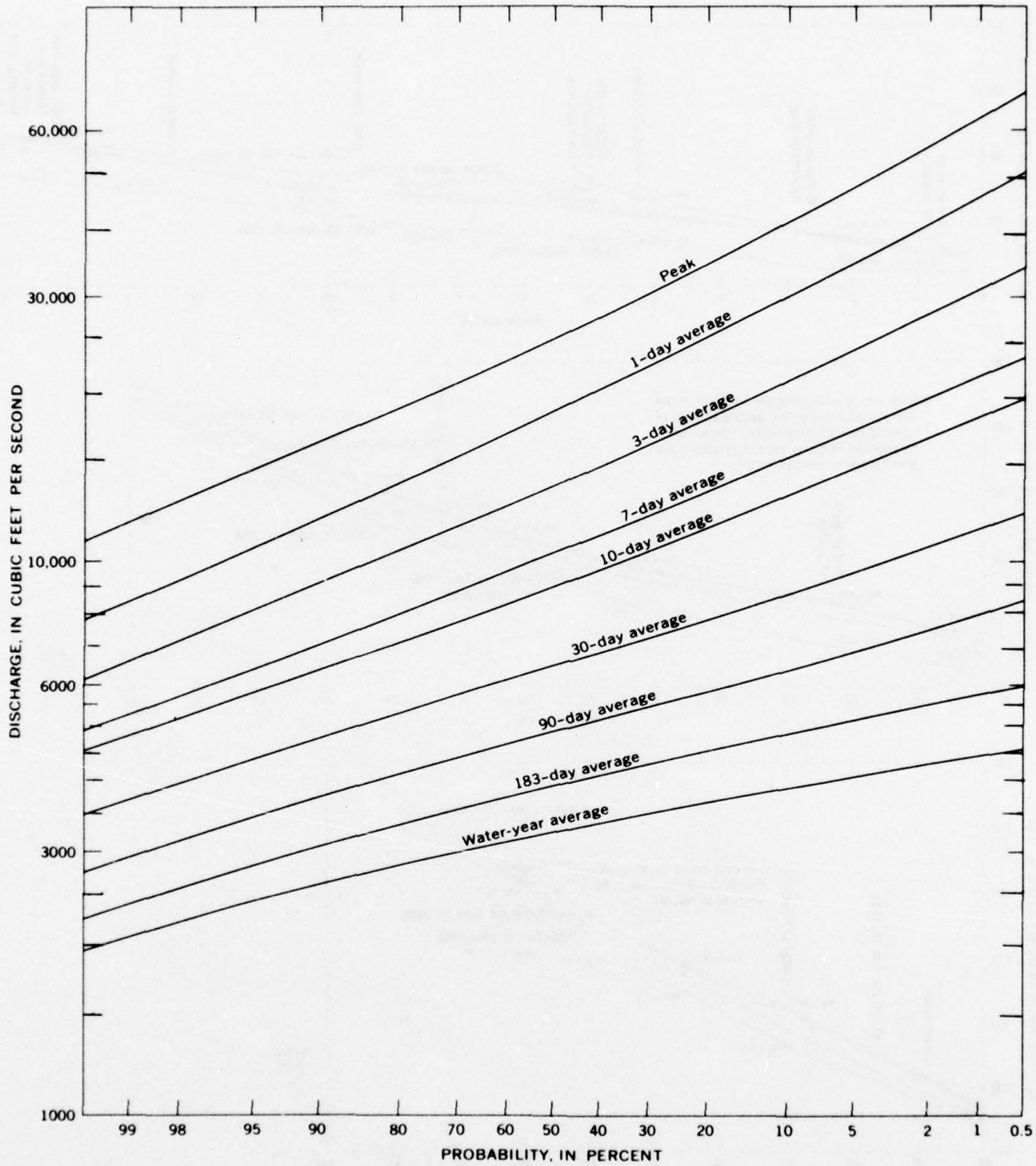


FIGURE 28.—Probability curves of annual maximum flows for specified time periods, Nooksack River at Deming.

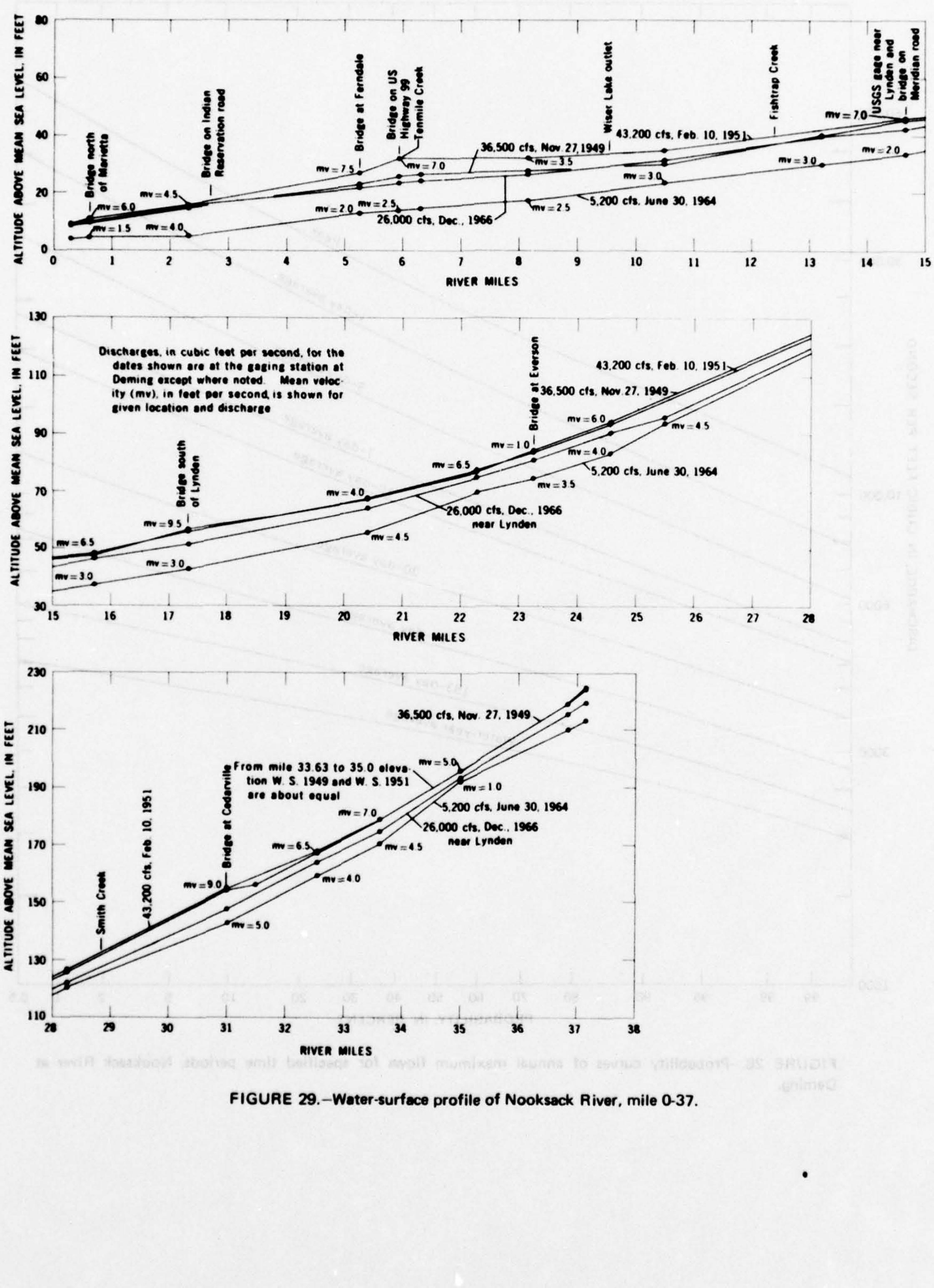


FIGURE 29.—Water-surface profile of Nooksack River, mile 0-37.

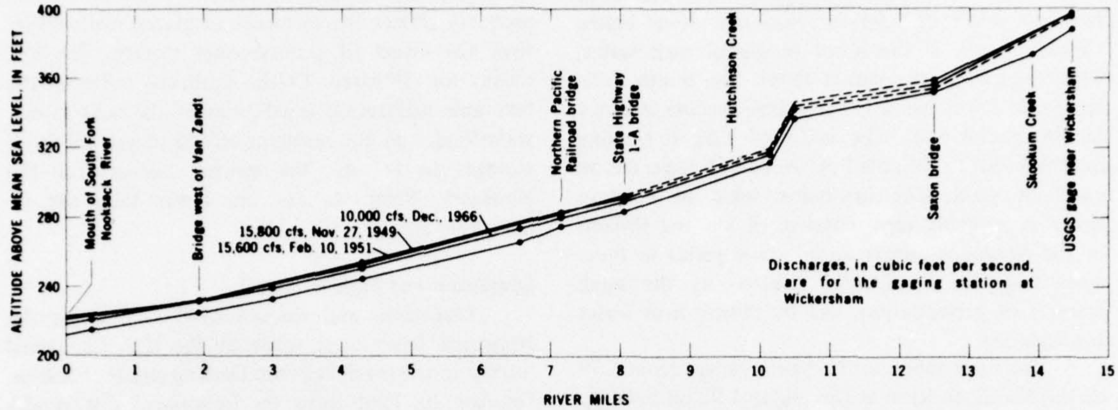


FIGURE 30.–Water-surface profile of South Fork Nooksack River, mile 0-14.

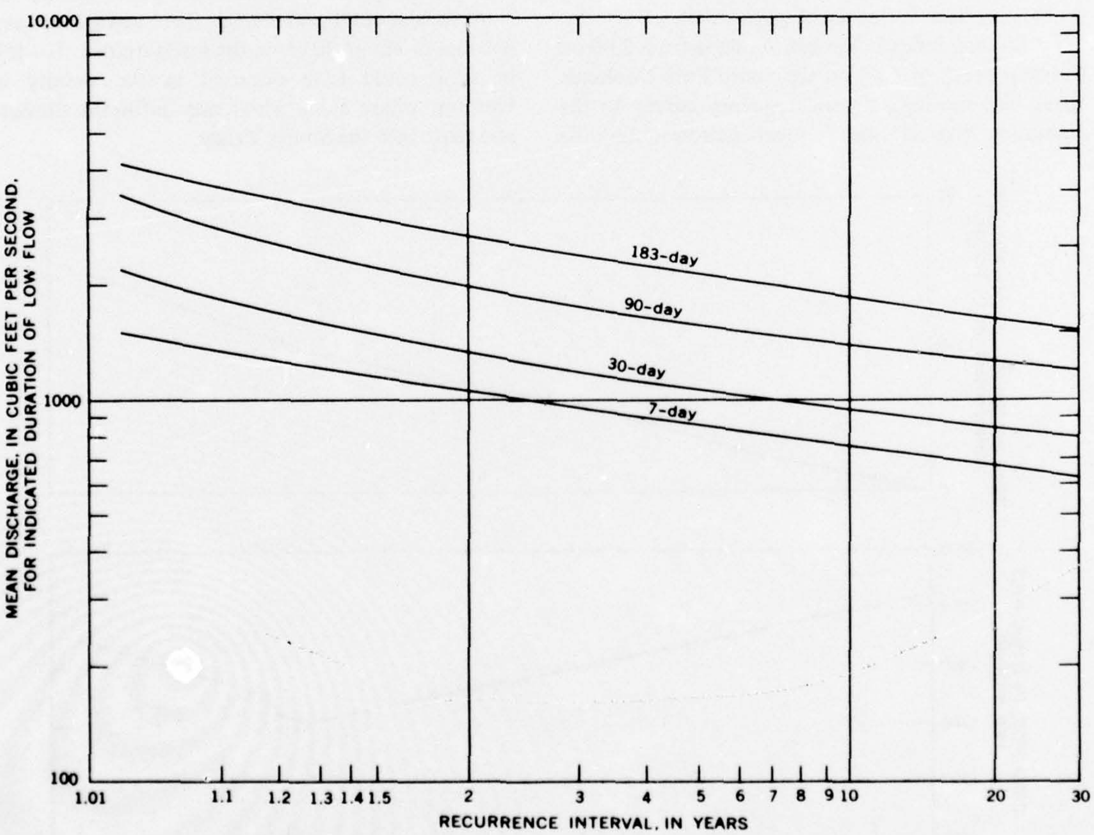


FIGURE 31.–Low-flow frequency, Nooksack River at Deming, 1946-63.

yield more than 1 cfs per square mile. The large low-flow index of 1.90 for Nooksack River below Cascade Creek is the result of glacial melt water, which supports dry-weather flows. The South Fork Nooksack River has a lower index, because it is not fed by glacial melt. The index of 1.81 at Deming indicates that the Middle Fork Nooksack River has an excellent yield. The low-index value of Fishtrap Creek is probably representative of lowland streams in the Nooksack-Sumas Basins. Low yields in these areas may be significantly affected by the small amount of precipitation, and by diversion of water for irrigation.

The slope index in the basins ranges from 1.59 on the Nooksack River at Deming to 1.92 on Fishtrap Creek. The high slope index for Fishtrap Creek, which indicates variable flow, is due in part to diversions for irrigation. Slope indexes for the main-stem stations imply a uniformity of flow that probably reflects influence of glacial melt.

Spacing index in the basins ranges from 2.40 on Fishtrap Creek to 4.54 on the South Fork Nooksack River. The spacing between frequency curves for the Nooksack River stations is much narrower than the spacing for the South Fork stations. These differences probably reflect the influence of glacial melt, rather than the effect of ground-water storage. The low index for Fishtrap Creek probably reflects the favorable infiltration capabilities of the soils in that watershed, and the resultant effects of ground-water storage. In general, the spacing indexes for the Nooksack River stations are lower than the region-wide average.

Dispersion and Time of Travel

Dispersion and time-of-travel studies for the Nooksack River were made by the U.S. Geological Survey in the reach between Deming and Ferndale on October 26, 1965 using the fluorescent dye, rhodamine B. Profiles of discharge and of travel time of maximum dye concentration are illustrated on Figure 32.

Discharge of the Nooksack River during the study was about 1,800 cfs, but there was an apparent net loss of about 70 cfs in the reach studied. The loss in flow could have occurred in the vicinity of Everson, where some water may infiltrate alluvium and move into the Sumas Valley.

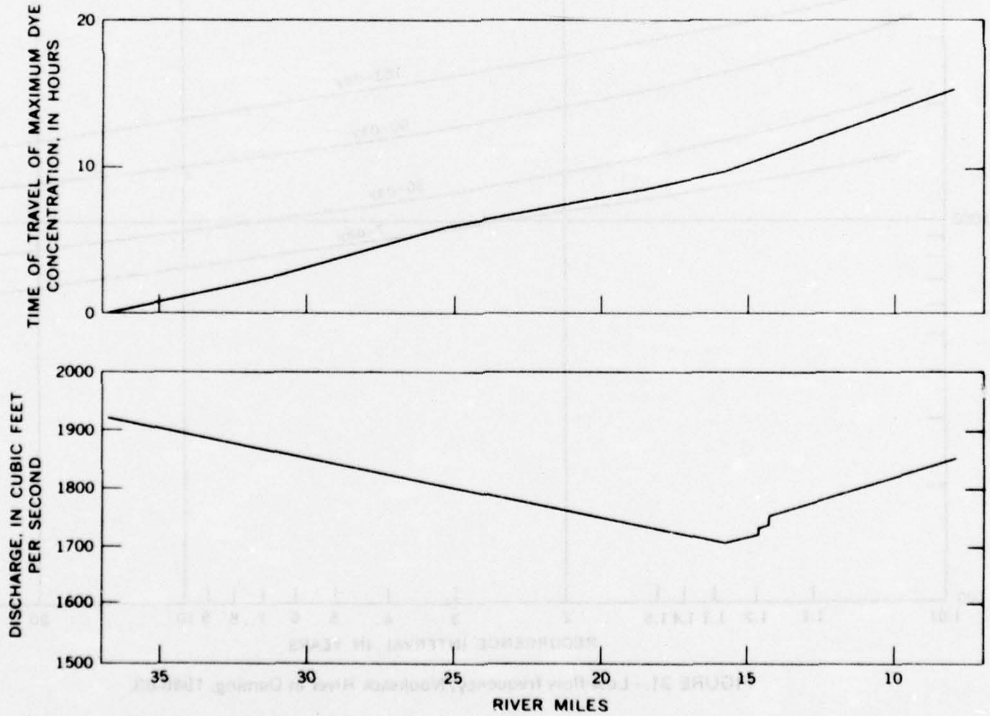


FIGURE 32.–Water discharge and time of travel of dye, Nooksack River, October 26-27, 1965.

The measured travel speed of the peak concentration decreased in the downstream direction. Near Deming, the travel time was about 26 minutes per mile, while near Ferndale it was about 43 minutes per mile. The average time of travel for the entire studied reach was about 33 minutes per mile.

Dispersion coefficients varied considerably, from 1,000 square feet per second in the Deming-Lynden reach to 400 square feet per second in the Everson-Ferndale reach. The values are anomalous to those for other streams investigated in the study area in that they are higher and decrease in the downstream direction.

STORAGE AND REGULATION

Natural Surface Storage

The total volume of storage in lakes and glaciers in the basins is not known, but surface areas can be used to provide at least a comparative indication of the amount of water that is stored. The total surface area of lakes in the basins is about 11.1 square miles, most of which is contributed by Lake Whatcom. Some of the storage in this lake has been created by a dam constructed at its outlet near Bellingham. The total surface area of glaciers in the basins is about 14 square miles, most of which is on Mount Baker and Mount Shuksan.

Reservoirs

The following discussions and tabulations of existing and potential reservoirs in the Nooksack-Sumas Basins are based mainly on water bodies containing more than 5,000 acre-feet. Existing reservoirs of smaller size are included only because of their local urban importance. Further discussion of small lakes is contained in Appendix XI, Fish and Wildlife. Existing reservoirs and potential storage sites in the basins are shown in Figure 33.

Existing Reservoirs—No major reservoir exists on the Nooksack River or its tributaries, so the flow of the river remains virtually unregulated. The Nooksack Falls power plant at Excelsior imposes a slight regulation at low flows, but the effect is negligible. The city of Bellingham has over 27,000 acre-feet of municipal and industrial storage in Lakes Padden and Whatcom. Storage totaling approximately 5,600 acre-feet for wildlife enhancement is found in Lake Terrell. Reservoirs on three lakes in the Nooksack-Sumas Basins provide an aggregate total storage of about 33,000 acre-feet (Table 17).

Potential Storage Sites—Table 18 presents data on the major potential reservoir sites in the Nooksack-Sumas Basins. Of the sites listed, the following are discussed in detail by the Washington Division of Water Resources (1960, p. 101–109): Deming, Shuksan, North Fork, Wells Creek, Skookum Creek, and Edfro Creek.

DIVERSIONS

The city of Bellingham diverts maximum of 102 cfs from the Middle Fork of the Nooksack River for municipal supply. Although the water appropriation permit for this project allows the city to develop facilities to divert up to 250 cfs, constant diversion at this latter rate is improbable because low flows of about 150 cfs normally can be expected at this location. In addition, the Department of Fisheries and Game have required that a minimum of 10 to 15 cfs shall bypass the diversion at all times. None of the water diverted is returned to the Middle Fork.

Flow in the lower reaches of the Nooksack River is reduced slightly by a 5 cfs diversion for the city of Lynden's municipal supply. A part of the water is returned to the Nooksack a short distance downstream from the diversion in the form of sewage-treatment plant effluent. A total of 25 cfs is diverted in two pipe lines at Ferndale by the Whatcom County Public Utility District No. 1 and the Mobil Oil Company. The Public Utility District diversion of 20 cfs is used by the Italco Aluminum Corporation. Both diversions are discharged to tidewater.

The largest diversion in the Nooksack-Sumas Basins is maintained by Puget Sound Power & Light Company for its Excelsior plant on the North Fork of the Nooksack River.The generating capacity of the installation indicates that the present diversion is about 125 cfs. The water is returned to the river a few hundred feet downstream.

The Washington Department of Fisheries Nooksack River Salmon Hatchery on Kendall Creek diverts 3+ cfs from Kendall Creek, which is returned below the hatchery ponds.

In 1965 diversions for irrigation in the basins, principally in the lower reaches of the Nooksack River, was estimated to be 5,900 acre-feet.

TABLE 17.—Existing reservoirs in the Nooksack-Sumas Basins

Use: R, recreation; WS, municipal and industrial water supply

Name	Location Stream, T-R-S	Drainage area (sq mi)	Storage-(Acre-ft) Active	Inactive and/or dead	Total	Dam dimensions Ht (ft)	Width (ft)	Reservoir area (acres)	Use	Applicant or owner	Remarks
Terrell Lk	Terrell Cr, 39-1-16	6.0			5,600	10	18	700	R	State of Wash. Dept. of Game	Fish and wildlife
Lk Padden	__ 37-3-8	__		__	780	5	73	152	WS	City of Bellingham	__
Lk Whatcom	Whatcom Cr, 38-3-28	55.9	__	__	26,400	5	100	5,003	WS	City of Bellingham	To be augmented from S. F. Nooksack

TABLE 18.—Potential storage sites in the Nooksack-Sumas Basins

Map no.	Project name	T-R-S	River and mile	Total storage (1000 acre-ft)	Drainage area (sq mi)
1	Deming	38-5-6	Nooksack 36.8	500	584
2	Welcome	38-5-33	Nooksack 40	104	395
3	Rocky Ridge	39-5-10	Nooksack 43.2	322	__
4	Maple Falls	40-6-31	Nooksack 49.4	6	180
5	Warnick	39-6-2	Nooksack 55.5	250	193
6	Glacier	39-7-2	Nooksack 61.6	32	95
7	Wells Cr.	39-8-4	Wells Cr 2.2	12	21
		39-8-9			
8	Shuksan	40-8-34	Nooksack 69	220	66
9	North Fork	40-8-32	Nooksack 66.4	194	70
10	Maple Cr.	40-6-30	Maple Cr.	18	
11	Heisler Ranch	38-6-18	M. F. Nooksack	__	__
12	Falls Cr.	38-6-20	M. F. Nooksack	__	__
13	Wanlick	36-6-22	S. F. Nooksack 25		37
14	Edfro Cr.	37-5-35	S. F. Nooksack 15.2	500	102
15	Skookum Cr.	37-5-27	S. F. Nooksack 14	500	103
16	Whatcom Cr. #1	38-3-28	Whatcom Cr		56

QUALITY OF SURFACE WATER

Chemical and Sanitary Quality

Chemical quality of surface water in the Nooksack-Sumas Basins is excellent; the water generally is acceptable for most uses.

The dissolved-solids content of surface waters in the basins rarely exceeds 100 ppm. Samples collected monthly from the Nooksack River at Ferndale during a 5-year period had a maximum dissolved-solids content of 77 ppm (Table 58). Shorter periods of record and spot sampling on the tributaries above Ferndale indicate that the upstream waters are even more dilute. The water in all streams is generally soft (hardness of 60 ppm or less), and hardness of more than 100 ppm is unusual.

Because the flow of the Nooksack River is supported substantially by glacial melt water, turbidity in the main stem is predictably high. Turbidity of the river at Ferndale has averaged 69 with a maximum of 700 JTU (Jackson Turbidity Units).

Sanitary quality of the waters is variable in both time and place. The higher concentrations of coliform bacteria occur during the summer, principally in reaches below the more populated areas. MPN values for coliform bacteria in samples from the Nooksack River at Ferndale reached a maximum of 24,000, with a mean of 2,100 during the 5 years of record for this site. A MPN value of 24,000 has also been recorded for a sample collected from the Nooksack River near Deming.

Stream Temperatures

Maximum and minimum monthly stream temperatures obtained from spot observations at four sites in the Nooksack-Sumas Basins are listed in Table 59. The data show that streams in these basins generally are cooler, both in summer and winter, than those elsewhere in the Puget Sound Study Area, possibly because these basins are the farthest north. The streams are virtually unregulated, and their temperatures reflect natural conditions. Freezing temperatures have occurred during winter months at all sites investigated. The North Fork Nooksack River is much cooler in the summer—by about 10°F—than the South Fork because of relatively large volumes of

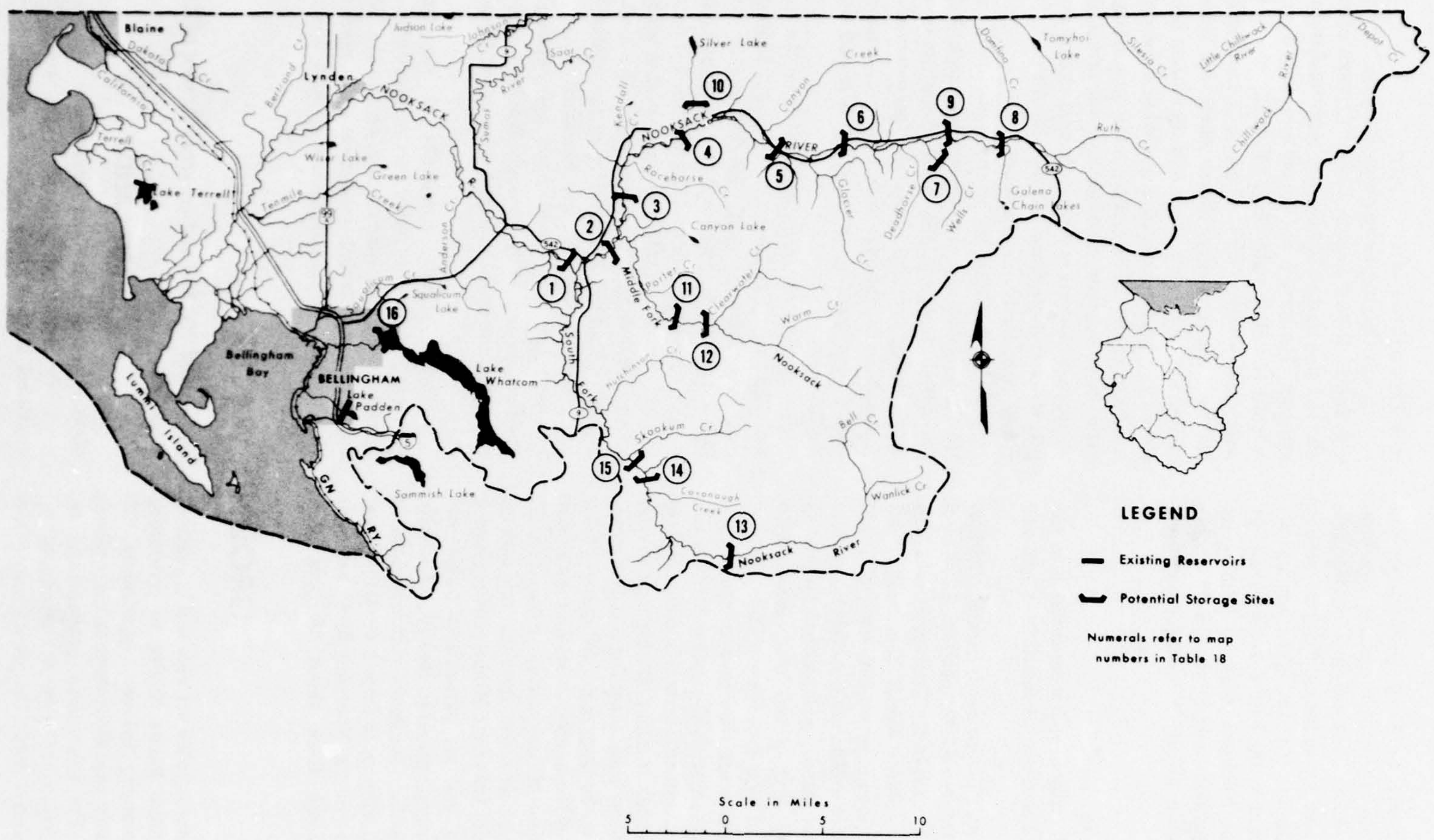


Figure 33. Existing Reservoirs and Potential Storage Sites in the Nooksack—Sumas Basins

cold water contributed by North Fork glacier and snowfields. In addition, the comparatively low summer flows in the South Fork permit a considerable warming of the water during transit. Temperatures on the South Fork—about 70°F during the summer—are the highest observed in the basins. Temperatures on the main stem of Nooksack River at Deming are about the same as those near Lynden. Both essentially reflect composite effects of the mountain tributaries.

Sediment Transport

Features of erosion and sedimentation in the Nooksack-Sumas Basins are discussed by upper and lower drainages.

The upper part of the basins includes the area upstream from Deming, where much of the land is rough and mountainous. In the three major valleys of the Nooksack River above Deming, soils on the flood plains consist of highly permeable sand, silt, and gravel. Erodability of soils in much of this area, where heavy precipitation occurs, is diminished by profuse vegetation. Where logging and road construction expose the soil, erosion can remove fine sediment during periods of intense rain. Because the streambanks contain large amounts of gravel and cobble and only small quantities of fine materials, sedimentation owing to bank erosion is minor. During high streamflows, however, some bank sloughing and bed movement is evident in the three major tributaries of the Nooksack. Most of the headwater streams are almost sediment free; they seldom contain more than 20 ppm. In contrast, glacier-fed streams that originate on the slopes of Mount Baker and Mount Shuksan have a milky appearance and are particularly turbid and sediment-laden during periods of high runoff, usually during warm weather. Sediment concentrations in these streams probably range from 1 to 60,000 ppm. In the three forks of the Nooksack River, sediment concentrations range from about 10 ppm to a probable maximum of 2,000 ppm.

Below Deming, flood plains along the Nooksack and Sumas Rivers contain alluvial deposits of clay, silt, and sand that are spread over recessional outwash materials. The terrace and upland areas have a variety of soils including tight clay, till, sandy glacial outwash, and gravelly drift. These soils have variable drainage characteristics. Where lands are recently cleared and cultivated, sheet and rill erosion occurs. Urban and road construction probably cause only a small part of the sedimentation in this area. Along the main river channels, alluvium becomes saturated to about river level and is subject to rapid erosion during periods of high discharge. Gravel and cobble bars are moved considerably during floods.

Fishtrap Creek is an example of a small tributary stream in the Lower Nooksack Valley. Though it transports only small quantities of sediment during normal flow, the presence of the denuded banks, and bars of sand and gravel, indicates that a large quantity of sediment is moved during higher flows.

Analyses of samples obtained from the Nooksack River near Lynden during 1965 and 1966 show that large sediment loads are transported during high-water periods. An annual load of about a million tons of suspended sediment can be expected during a year of normal runoff. The daily load is probably about 300,000 tons when the daily river discharge averages about 30,000 cfs. During the winter, sediment concentration in the Nooksack River near Lynden range from 50 to 3,000 ppm. During the low-flow period (July through October) sediment concentration is low, ranging from about 20 to 50 ppm.

Under present conditions in the basins, sediment problems are minor except, where erosion is caused by logging, construction, or farming. Where banks are unprotected, productive land adjacent to river channels is occasionally lost by bank sloughing.

GROUND WATER

Ground-water supplies are plentiful in much of the Nooksack-Sumas Basins. Owing to contrasting geologic environments, however, significantly different ground-water conditions exist in the lowlands and mountains. For this reason, ground-water resources in the basins are discussed separately, by lowland and mountain areas. The lowlands are below altitudes of 800 feet and are generally west of Sumas Mountain.

LOWLANDS

Geology and Ground-Water Occurrence

The important aquifers in the lowlands are contained in Quaternary sediments which are rather

continuous over about 350 square miles. The sediments thicken to the west and north, and they pinch out against older consolidated rocks to the east and south. In the north, some of the deposits locally may be over a thousand feet thick. In most places in the lowlands, ground water can be obtained from depths less than 100 feet below land surface and practically all fresh-water aquifers are at depths less than 300 feet below sea level.

Quaternary sediments exposed at the surface are mainly till, recessional outwash, and alluvium. Till caps the uplands which are located principally east of Blaine, west of Custer and Ferndale, and north of Bellingham. Till also forms the surface of Point Roberts and the northern part of Lummi Island. Till occurs at depth and is overlain by other deposits throughout most of the valley areas. Although till normally is less than 30 feet thick, it exceeds 50 feet locally. Till is composed largely of fine materials; it does not contain important aquifers but over large areas it transmits appreciable quantities of water to underlying aquifers.

Recessional outwash occurs extensively throughout most of the valleys, and on the higher terraces that are till-capped. Where recessional outwash occurs on the uplands it is in the form of isolated deposits that contain little water. The recessional outwash deposits almost everywhere are less than 100 feet thick. Where they occur in the valleys they contain abundant but discontinuous beds of water-bearing sand and gravel, which are thickest and coarsest in the vicinity of Lynden and Sumas.

Recent alluvium occurs mostly on the flood plains and deltas of the Nooksack River and its tributaries. On flood plains above Ferndale, alluvium is not easily distinguished from the underlying recessional outwash. The uppermost 100 feet of sediments are fine sand, clay, silt and occasional gravel beds that become more plentiful to the east. Alluvial sediments are finer grained on the Nooksack delta, where they thicken to 300 feet or more. Alluvium is saturated about to river level.

Quaternary sediments older than till are rarely exposed. They are extensive at depth, however, and they contain sand and gravel aquifers at most places. The aquifers become thicker and contain coarser materials to the east, but their aggregate thickness is no more than 40 feet. To the west the aquifers generally contain saline water at depths greater than about 200 feet below sea level. The aquifers are confined under artesian pressure, except at higher altitudes where upper zones of sediments older than till are, in general, above the water table.

Practically all recharge to the aquifers is by infiltration of precipitation. Aquifers in the lowlands are conservatively estimated to receive about 50,000 acre-feet of recharge in an average year. In addition, significant amounts of ground water enter the basin by underflow across the International Boundary west of the Sumas Valley (Washington Division of Water Resources, 1960, p. 3).

Induced recharge may be feasible along the flood plain of the Nooksack River upstream from Ferndale. The trough occupied by the Sumas River seems promising for artificial recharge, but some of the water might be lost to Canada because the ground- water flow is toward the north in the Sumas River valley.

The natural discharge of ground water is mostly into the Nooksack River and its tributaries, and into bays through submarine springs.

Quality of Ground Water

Water in most lowland aquifers is reasonably low in dissolved solids and acceptable for many uses. Dissolved solids content generally is less than 200 ppm except in areas near bays, where saline water occurs in some aquifers. Significant encroachment of sea water has not as yet been detected. Hardness of the ground water is commonly in the 60 to 120-ppm range, and silica generally ranges from 20 to 40 ppm. Objectionable concentrations of iron are common, particularly in shallow aquifers.

Utilization and Development

Ground water pumped in the lowlands is used mostly for irrigation. This is particularly true in central and northeastern areas, where the water is obtained mostly from aquifers in recessional outwash. The municipal and industrial use of ground water is principally in the western part of the basins, where the water is pumped from subtill aquifers.

Figure 23 shows approximate estimates of expected well yields in the study area. The largest yielding wells produce water from recessional outwash; they are usually no deeper than 50 feet. Some of these wells produce more than 1,000 gpm. Deeper wells completed in aquifers older than till are generally not capable of producing more than 500 gpm.

Adequate ground-water supplies are difficult to obtain in the southern part of the basins where

Quaternary deposits are thin. Other areas of inadequate production are Lummi Island, Point Roberts, and the Lummi Peninsula. In areas within about 2 miles of the shoreline, aquifers that contain water of suitable quality are rare.

Where subtill aquifers are tapped in the lower Nooksack Valley and in the valley of Anderson Creek, wells may flow as much as 500 gpm.

MOUNTAINS

In the mountains, ground water is abundant only in valleys of major tributaries to the Nooksack River, where wells completed in alluvial aquifers there yield as much as 500 gpm. Alluvial deposits of this type are notably extensive in the valley of the South Fork. Large amounts of precipitation and runoff from adjacent valley slopes suggest that the alluvial aquifers receive relatively large amounts of recharge.

In areas where Quaternary sediments are absent, ground water is obtainable only from consolidated rocks, in which well yields of only 10 gpm or less can be expected.

SKAGIT—SAMISH BASINS

SURFACE WATER

The Skagit-Samish Basins comprise an area of 3,184 square miles, including 3,044 square miles of land and inland water. A map of the basins is shown in Figure 45. The largest stream in the area, the Skagit River, drains 3,105 square miles, of which about 400 are in Canada (the drainage area in Canada is outside the study region). The major tributaries of the Skagit River are the Baker, Cascade, and Sauk Rivers. The Suiattle River is a large and important tributary of the Sauk River. The Skagit River and its major tributaries have their headwaters in the mountainous areas of the North Cascade Range, where the flow of many streams is in part derived from melting glaciers. The Skagit River is joined by the Cascade River near Marblemount. Below Marblemount, it flows through broad, mountain-bordered flood plains to the large glacial outwash plain in the vicinity of Sedro Woolley. In the lowland areas, the river meanders for several miles until, at a point about 8 miles from Puget Sound it branches into two major distributaries which flow into Skagit Bay. The average annual discharge of the Skagit River into the Bay was about 11,800,000 acre-feet during the period 1931-60 (includes basin drainage from Canada, outside the study area).

The Samish River, north of the Skagit River basin, has its headwaters in rough upland terrain south of Bellingham. Friday Creek, the outlet of Samish Lake, is the main Samish tributary. From Friday Creek, the Samish River descends in a short distance to a broad glacial outwash and alluvial plain, flows in a southerly direction for about 8 miles, and then courses west and north to its outlet at Samish Bay near Edison. Drainage area of the Samish River is about 106 square miles, and its average annual runoff is about 193,000 acre-feet.

Most surface-water storage in the Skagit-Samish Basins is in Ross and Diablo Lakes and in the two reservoirs on the Baker River. Extensive snowfields provide large amounts of seasonal storage. A significant perennial storage is also provided by glaciers on the higher peaks of the North Cascade Range.

STREAMFLOW

Runoff Characteristics

The Skagit River produces more runoff than any other river basin in the Puget Sound Area. Although about 13% of the watershed is in Canada, all but about 6% of the average annual runoff originates within the State of Washington. In the mountain areas, average annual runoff exceeds 140 inches at the headwaters of the Baker, Cascade, and Suiattle Rivers. Because of the shielding effect of Mount Baker, Mount Shuksan, and the Pickett Range, the runoff in upper reaches of the Skagit River main stem is only about 38 inches annually. Similar conditions prevail in the lower reaches of the Sauk River drainage, where the average annual runoff is about 60 inches.

The least runoff in the basins occurs in the lowlands west of Mount Vernon and on outlying islands, where the average annual runoff is probably less than 15 inches. Average runoff for the entire Skagit-Samish Basins is about 71 inches annually or 11,500,000 acre-feet.

Most of the Canadian contribution has been gaged at a site on the Skagit River about 4 miles north of the International Boundary. The mean annual discharge at this site, adjusted to the 1931-60 base period, is 1,000 cfs, or 724,000 acre-feet per year. The unit discharge in the Canadian part of the basin is only about 2.8 cfs per square mile. Downstream, unit-area contributions of tributary streams gradually increase. For example, the average annual unit discharge of Thunder Creek is about 5.9 cfs per square mile, and farther downstream the Cascade River watershed produces 6.2 cfs per square mile. The overall average for the Skagit Basin increases downstream, as indicated by streamflow records for the Skagit River at Newhalem (3.8 cfs per square mile), and near Marblemount (4.2 cfs per square mile). The average annual runoff at Marblemount for the period 1931-60 is about 3,860,000 acre-feet.

Although the Sauk and Suiattle River catchments are not favorably oriented relative to prevailing storm winds, the comparatively high mountain barriers along watershed divides, and the high slopes of Glacier Peak, serve to capture large quantities of precipitation. Runoff per square mile in this area is generally greater than in the upper Skagit watershed to the north. Above the White Chuck River, the 30-year average discharge of the Sauk River is 1,140 cfs, or 7.5 cfs per square mile of drainage area. For practically all of the Sauk-Suiattle River system, the mean annual discharge is 4,390 cfs, or about 6.1 cfs per square mile. The average runoff contribution for this area is about 3,180,000 acre-feet per year.

The southwesterly exposed Baker River watershed is rimmed by several major peaks, and presents an excellent catchment for precipitation, thereby producing large quantities of runoff. The 30-year average discharge of the Baker River is 2,590 cfs, or 8.7 cfs per square mile. In terms of runoff production, the discharge is equivalent to 1,870,000 acre-feet per year.

The discharge of Skagit River below the mouth of Baker River is not increased appreciably by tributary contributions. In the 30-mile reach between Concrete and Mount Vernon, the average discharge of the Skagit River increases from 15,100 to only 16,200 cfs. The discharge records at Mount Vernon essentially represent the total flow of the Skagit River. Adjusted to the period 1931-60, the average annual runoff at Mount Vernon is 11,800,000 acre-feet. The average unit discharge for the entire basin is 5.2 cfs per square mile.

The annual runoff record for the Skagit River near Concrete is presented in Figure 34. The highest recorded annual discharge of the Skagit River, as shown by the record for the Concrete site, occurred in the 1934 water year and was 131% of the 30-year average. The lowest recorded runoff was about 64% of the average and occurred in the 1944 water year.

Characteristics of average monthly streamflow for the river and some of its tributaries are shown in

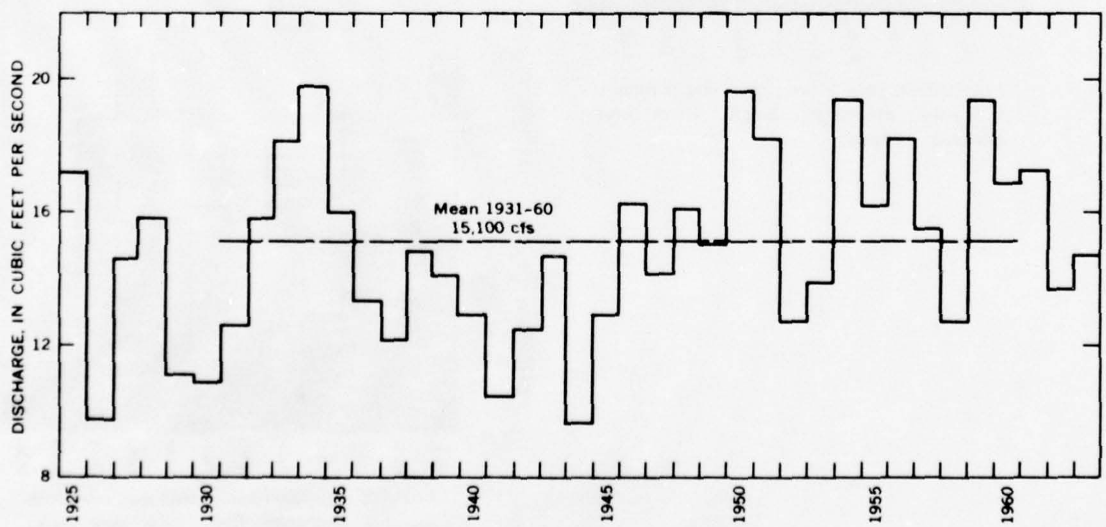


FIGURE 34.—Annual discharges, Skagit River, near Concrete.

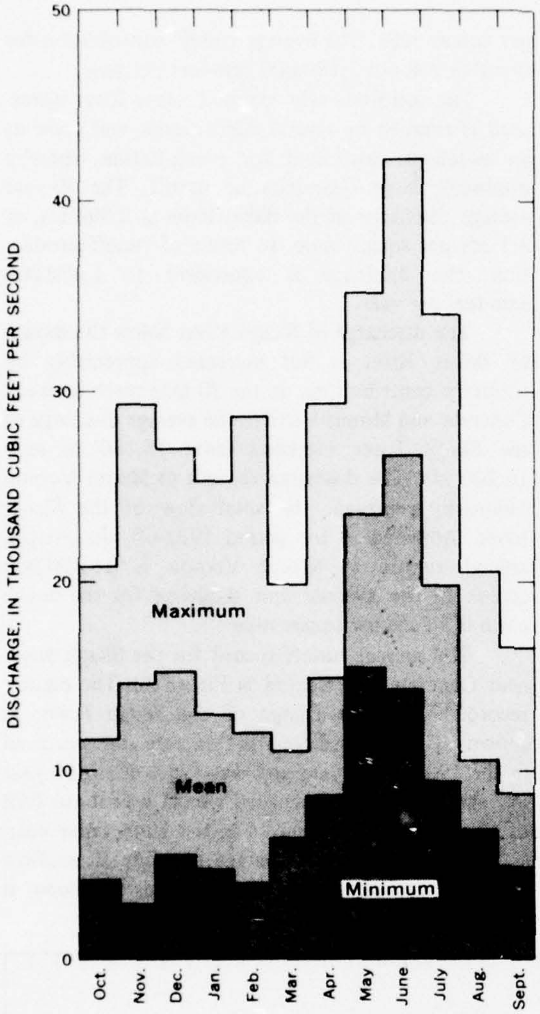


FIGURE 35.–Maximum, mean and minimum monthly discharges, Skagit River near Concrete, 1931-60.

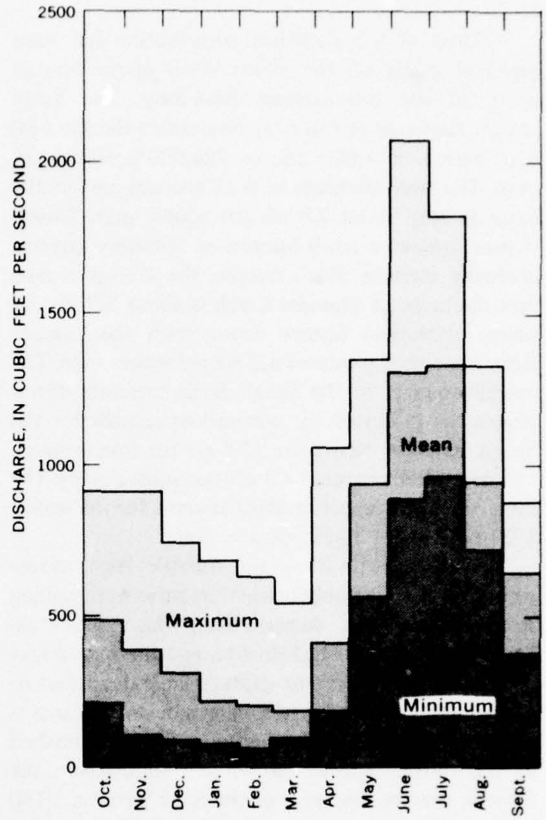


FIGURE 36.–Maximum, mean and minimum *monthly* discharges, Thunder Creek near Newhalem, 1931-60.

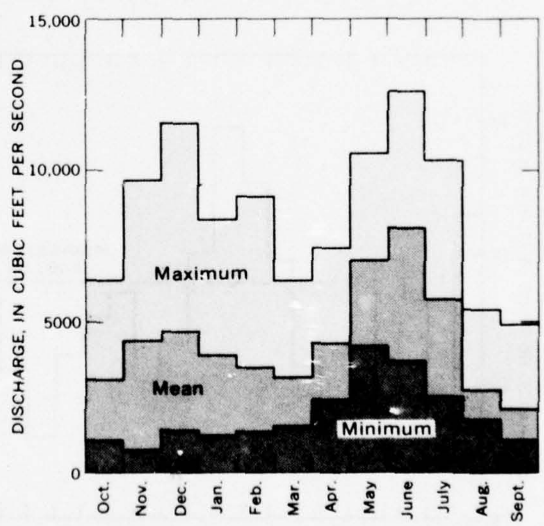


FIGURE 37.–Maximum, mean and minimum monthly discharges, Sauk River near Sauk, 1931-60.

Figures 35, 36, and 37. These streams display the winter and spring peak-flow periods that are characteristic of many streams draining the western slopes of the Cascade Range. However, the spring snowmelt peaks are more pronounced in the Skagit Basin than elsewhere. In the Canadian part of the Skagit watershed, most winter precipitation is received in the form of snow, and is stored until spring. Other high-elevation tributary watersheds have similar characteristics; in fact, on Thunder Creek, a winter peak runoff is rare. The highest monthly discharges at the selected stream-gaging sites in the Skagit Basin normally occur during the month of June.

Numerous glaciers in the basins regulate stream discharge by practically eliminating extreme low flows during dry summer months. Ground-water in-flow along lower reaches of the Skagit and its major tributaries increases the low-flow discharge, as do releases from storage in the major reservoirs on the upper Skagit and Baker Rivers. In the watersheds at higher altitudes, the minimum monthly runoff occurs about February of March, but at lower altitudes the minimum flow in tributary streams normally occurs in September.

Streamflow characteristics of the Skagit River at the stream-gaging site near Concrete are representative of the main stem and some of its major tributaries. Runoff at the Concrete gage is from an area of 2,737 square miles, which is 88% of the Skagit Basin. Streamflow usually begins to increase in September or October from the summer base flow of approximately 9,000 cfs. From October to March, the streamflow is characterized by a series of sharp rises superimposed on a base flow which is highest in December. Because of regulation by power-production reservoirs on the upper Skagit and on Baker River, higher-than-natural base flows occur during October-March, and lower-than-natural base flows occur during the spring months, when the reservoirs are being filled. Runoff generally decreases during the period December-March as a result of colder weather. As temperatures begin to rise in April, snowmelt causes increased streamflow, which usually reaches an average discharge of about 25,000 cfs near Concrete by the middle of June. Following the snowmelt peak, streamflow recedes to minimum base flows, usually by the end of August, as the snowpack is depleted. At this time, discharge is sustained by contributions from ground-water storage and melting glaciers.

The variability of the daily flow of streams in the Skagit-Samish Basins is presented as flow-duration data for selected gaging stations in Table 19.

Flood Characteristics

Floods caused by excessive rainfall and accompanying snowmelt are shown by characteristic sharp rises on a hydrograph, followed by recessions almost as rapid. Two or more flood peaks often occur within a period of two weeks. However, flood-control storage in Ross Reservoir has reduced the magnitude of floods on the Skagit River since 1941. Discharge is seldom above the zero-damage level (60,000 cfs near

TABLE 19.—Flow-duration data for selected gaging stations in the Skagit-Samish Basins

Gaging station	Period of analysis	Flow, in cubic feet per second, which was equaled or exceeded for indicated percent of time											
		99	95	90	80	70	50	30	20	10	5	1	0.1
Skagit River near Hope, B.C.	1935-55	110	152	185	245	315	510	920	1,420	2,500	3,500	5,550	8,500
Big Beaver Creek near Newhalem	1941-48	80	97	110	140	171	265	430	560	790	1,010	1,580	2,400
Skagit River near Newhalem	1931-39	400	525	640	840	1,060	1,700	3,050	4,350	6,300	8,000	11,000	16,000
Ruby Creek below Panther Creek near Newhalem	1949-56	69	95	125	176	220	340	700	1,300	2,100	2,700	4,000	5,500
Ruby Creek near Newhalem	1931-48	75	99	118	150	185	290	590	1,000	1,700	2,300	3,500	5,800
Skagit River below Ruby Creek near Newhalem	1920-30	500	650	790	1,030	1,250	1,900	3,200	4,600	7,200	9,800	16,000	23,000
Thunder Creek near Newhalem	1931-64	76	105	129	175	232	440	810	1,050	1,350	1,650	2,350	3,700
Thunder Creek near Marblemount	1920-30	68	102	135	185	240	450	850	1,120	1,470	1,750	2,300	4,000
Stetattle Creek near Newhalem	1934-64	22	33	43	60	78	125	210	282	400	510	780	1,500
Skagit River above Alma Creek near Marblemount	1951-64	1,800	2,800	3,350	4,000	4,450	5,200	6,100	6,900	8,500	10,500	16,000	23,000
Cascade River at Marblemount	1929-65	178	270	335	435	530	770	1,170	1,520	2,080	2,600	3,750	6,300
Sauk River above Whitechuck River near Darrington	1929-65	163	225	282	390	510	820	1,340	1,740	2,360	2,980	4.500	8,700
Sauk River near Sauk	1929-65	820	1,250	1,500	1,900	2,350	3,400	5,000	6,250	8,300	10,200	15,500	30,000
Alder Creek near Hamilton	1944-65	6.6	8.3	9.7	12.5	15.5	26.5	42	53	72	92	164	320
Day Creek near Lyman	1944-60	11.5	18	26	50	83	170	290	390	600	860	1,650	3,000
Skagit River near Sedro Woolley	1909-19 1922-23	4,[illegible]00	5,200	6,000	7,200	8,500	12,000	18,200	23,000	31,500	40,000	62,000	115,000
East Fork Nookachamps Creek near Clear Lake	1944-50, 1963	1.5	3.0	5.0	10.5	21	50	90	122	192	300	670	1,500
Samish River near Burlington	1944-65	20	26	30	44	71	165	285	375	540	740	1,350	2,900

Concrete) for longer than 72 hours. The maximum discharge near Concrete, 154,000 cfs, was recorded on November 27, 1949.

Flood-frequency curves for the Skagit River near Concrete and Mount Vernon are presented in Figures 38 and 39. The periods of record at the Concrete and Mount Vernon gages are 1924-64 and 1940-64, respectively. Streamflow has been regulated for power and flood control since 1925 by reservoirs on the Baker River and since 1924 by reservoirs on the Skagit River. The effects of regulation by these reservoirs are included in the frequency data.

The ability of a stream to transport large quantities of water without causing damage depends on channel characteristics. These features can be characterized in part by a graphical representation of the stream's water-surface profile for various rates of discharge.

Profiles for the Skagit River shown in Figure 40 were plotted from observed or computed data. The velocities were obtained from backwater computations. The profile for 310,000 cfs near Concrete was drawn with data from stage-discharge rating curves. This profile coincides with the observed high-water profile for 1951 at about mile 18.5, indicating that a levee failure in the Burlington area probably would allow floodwater to flow into the Samish Basin and Swinomish Channel. The profile for 56,000 cfs at Concrete was drawn from observed data, and represents a condition slightly higher than bank full. The Skagit River has no abrupt changes in gradient between the mouth and river mile 66.

The Samish River profiles shown in Figure 41 were drawn from observed or computed data (values of velocity are not readily available). The upper profile for 52,900 cfs downstream from river mile 7.17, was constructed from rating curves and represents overflow from the Skagit River near Burlington. The Samish River has no abrupt changes in gradient between the mouth and river mile 12.

Low-Flow Characteristics

Low-flow characteristics of streams in the Skagit-Samish Basins are compared using indexes from low-flow frequency curves at 25 gaging stations (Table 20). Low-flow indexes are excellent for the tributaries located in the middle part of the basin such as Baker, Sauk, and Cascade Rivers (Fig. 22). They are good in Beaver, Thunder, and Suiattle Creek Basins, fair in the upper Skagit River Basin and part of the lower basin, and poor in the low-lying streams in the area adjacent to Puget Sound. Fairly large differences occur in the slope and spacing indexes in the basin. In general, the low-lying streams have much larger indexes than those for the tributaries in the upper part of the basin. These values showing the variability of low flows are greater than the study region average for the low-lying streams, and less than average for the upper tributaries.

Low-flow frequency data at the 25 sites are listed in Table 21. Frequency curves for 3 of the 25 stations are shown in Figures 42, 43 and 44.

The low-flow indexes in the basins range from 0.06 cfs. per square mile for Friday Creek, a tributary to the Samish River, to 2.75 cfs. per square mile for the Baker River. The low-flow index for the Baker River watershed is higher than any other in the Puget Sound region, this is attributed to the effects of glacier melt water and large amounts of storage in snowpacks. Small indexes (less than 0.50) are characteristic of the streams that drain the lowlands areas. The indexes shown by these streams may be the result of low precipitation and small contributions from ground-water discharges or losses to ground-water storage.

On the main stem of the Skagit River, the low-flow index in the Canadian watershed areas is small, and becomes progressively greater downstream. Low-flow indexes for discharge-measurement sites below Newhalem are greater than 2.00 cfs. per square mile. These large values are the result of regulation and large contributions by the Cascade, Sauk, and Baker Rivers.

Slope index in the basins ranges widely, and shows the effects of varying basin chacteristics. On the main stem of the Skagit River, the slope indexes are low, indicating little variability of low-flow from year to year; this is principally a result of regulation by reservoirs. Indexes greater than 2.0 for Finney, Day, Friday, and East Fork Nookachamps Creeks indicate the small contributions from ground-water storage in lowland basins.

Spacing index ranges from 1.89 in the Alder Creek watershed to 13.5 in East Fork Nookachamps Creek basin. The low value for Alder Creek is attributed to the effect of storage in porous alluvial deposits. A low-spacing index is also characteristic of basins that contain glaciers. The small values on the main stem of the Skagit River reflect regulation by reservoirs.

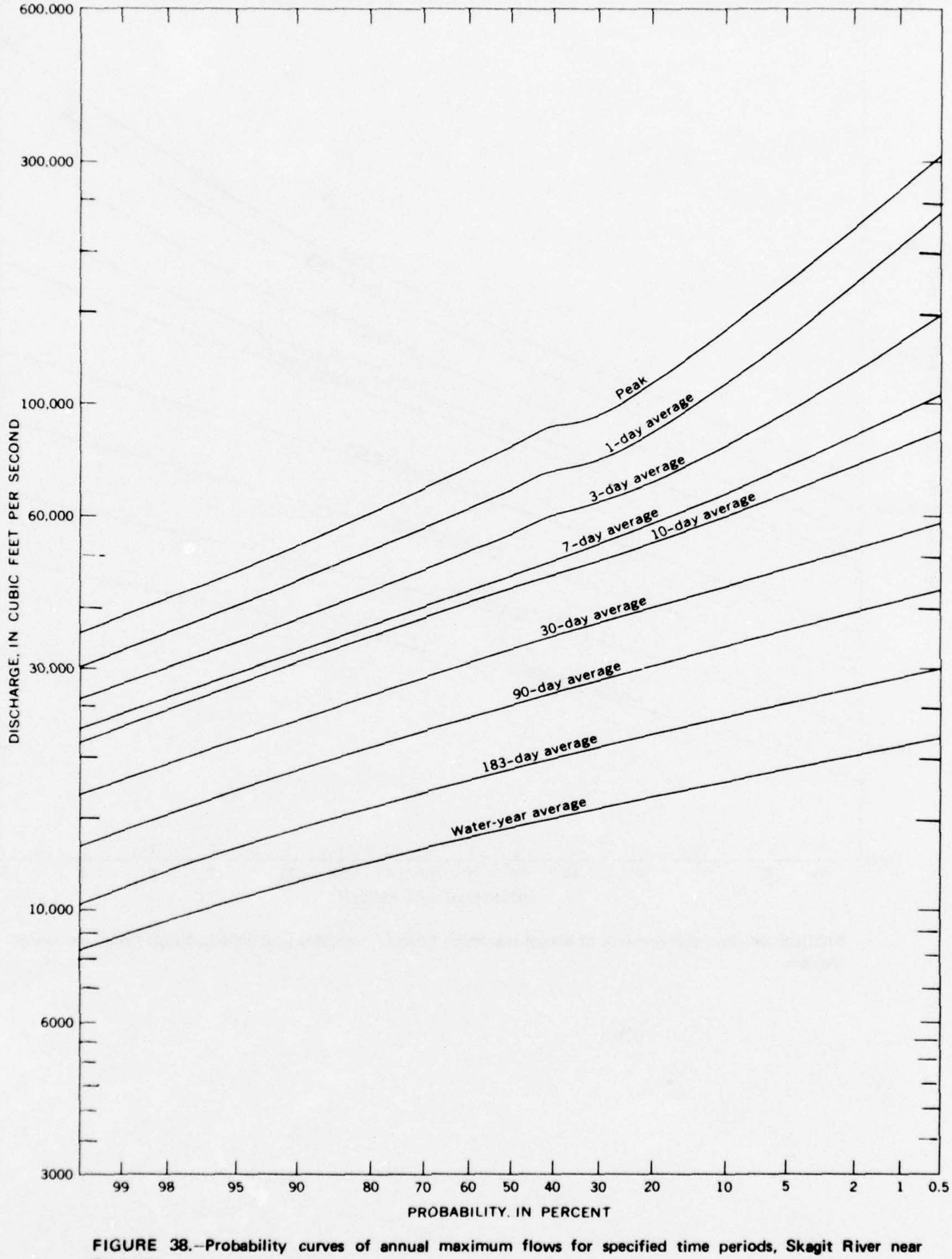


FIGURE 38.—Probability curves of annual maximum flows for specified time periods, Skagit River near Concrete.

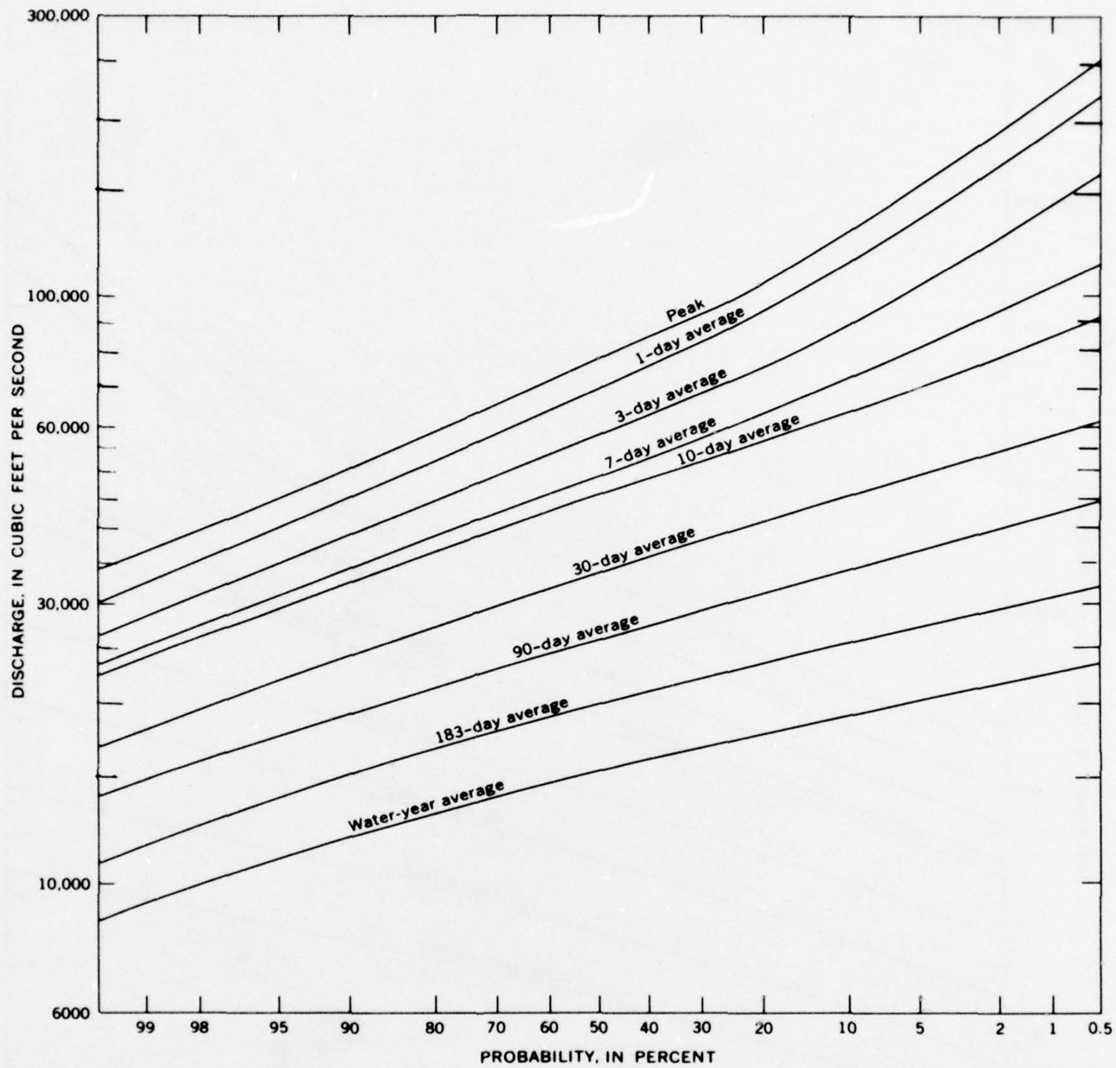


FIGURE 39.—Probability curves of annual maximum flows for specified time periods, Skagit River near Mount Vernon.

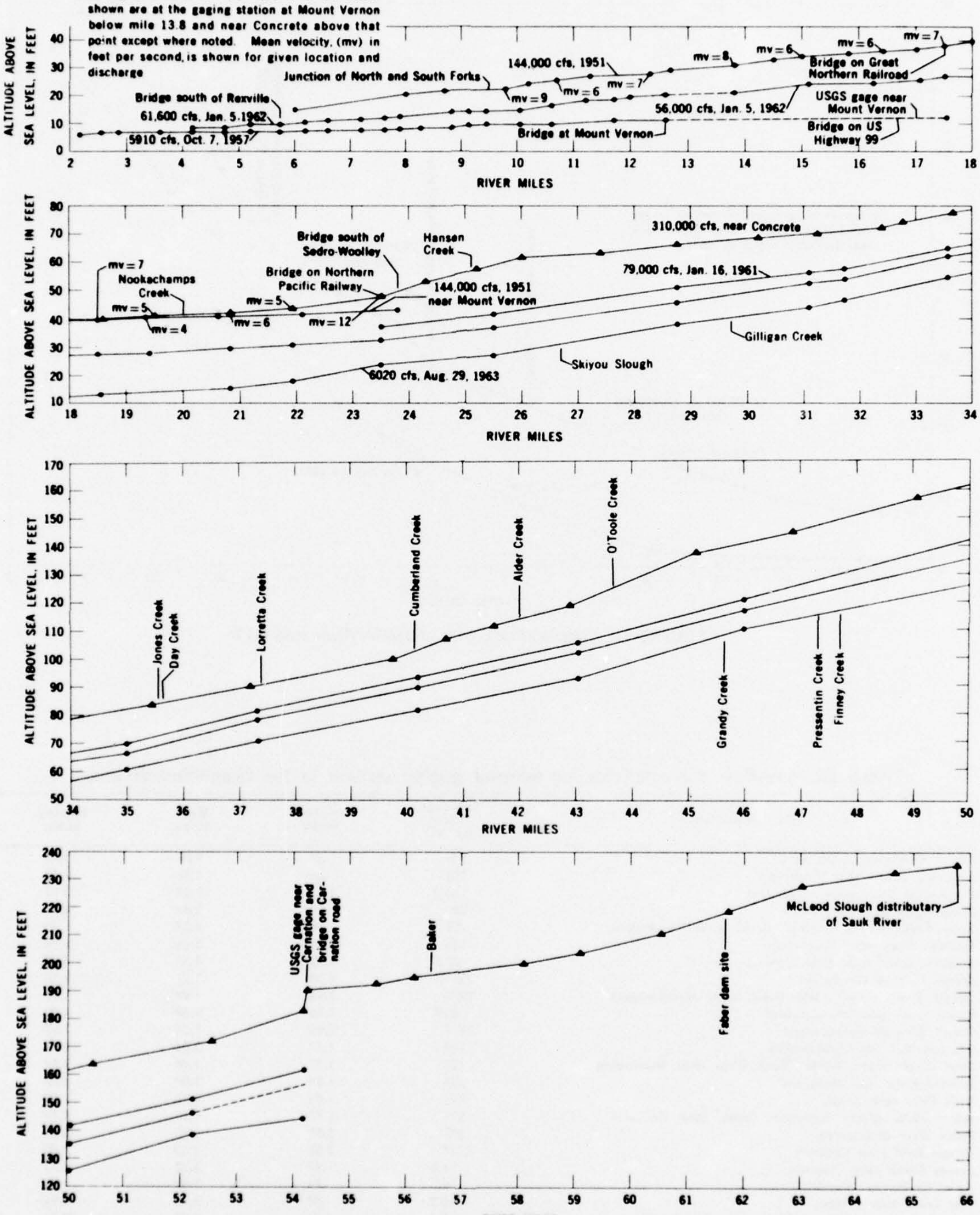


FIGURE 40.—Water-surface profile of Skagit River, via North Fork, mile 2-66.

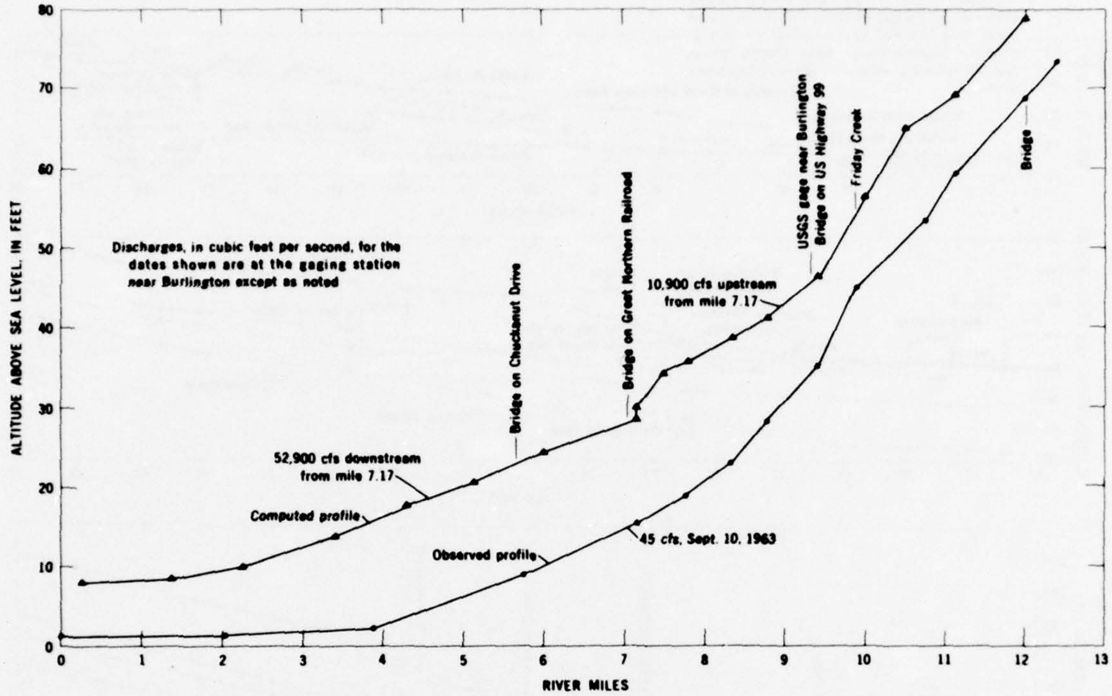


FIGURE 41.—Water-surface profile of Samish River, mile 0-12.

TABLE 20.—Low-flow characteristics for selected gaging stations in the Skagit-Samish Basins

Gaging station	Drainage area (sq mi)	Low-flow index	Slope index	Spacing index
Skagit River near Hope, B. C.	357	.57	1.33	2.45
Lightning Creek near Newhalem	129	.60	1.85	2.18
Big Beaver Creek near Newhalem	63.2	1.42	1.64	2.94
Skagit River near Newhalem	780	.96	1.64	2.11
Ruby Creek above Panther Creek near Newhalem	206	.46	1.59	3.35
Thunder Creek near Newhalem	105	1.02	1.64	2.99
Stetattle Creek near Newhalem	22.0	1.32	1.54	4.56
Skagit River at Newhalem	1175	1.66	1.77	2.10
Skagit River above Alma Creek near Marblemount	1274	1.96	1.92	1.96
Bacon Creek near Marblemount	50.9	1.90	1.59	4.02
Skagit River at Marblemount	1381	2.06	1.58	1.97
Cascade River at Marblemount	168	1.67	2.04	2.78
Sauk River above White Chuck River near Darrington	152	1.52	1.41	3.87
Suiattle River near Mansford	335	1.85	1.59	2.26
Sauk River near Sauk	714	1.82	1.79	2.73
Baker River above Anderson Creek near Concrete	211	2.75	1.67	2.93
Baker River at Concrete	297	2.57	1.75	2.86
Skagit River near Concrete	2737	2.37	1.55	2.00
Finney Creek near Concrete	51.6	.47	2.22	6.73
Alder Creek near Hamilton	10.7	.84	1.67	1.89
Day Creek near Lyman	34.2	.57	2.44	6.92
East Fork Nookachamps Creek near Clear Lake	20.5	.11	2.86	13.5
Skagit River near Mount Vernon	3093	2.33	1.56	1.97
Friday Creek near Burlington	37.1	.06	2.00	7.08
Samish River near Burlington	87.8	.30	1.47	3.19

TABLE 21.—Low-flow frequency data for selected gaging stations in the Skagit-Samish Basins
[Discharge adjusted to base period April 1, 1946, to March 31, 1964]

Gaging station	Number of consecutive days	Streamflow in cfs, for indicated recurrence, intervals, in years						
		1.05	1.30	2.0	5	10	20	30
Skagit River, near Hope, B. C.	7	340	245	200	163	152	145	140
	30	440	300	230	190	175	165	160
	90	610	420	320	240	218	200	190
	183	980	660	490	350	290	250	230
Lightning Creek near Newhalem	7	110	92	78	60	50	42	38
	30	142	110	88	65	55	48	44
	90	190	142	111	80	66	55	52
	183	310	223	170	125	108	96	90
Big Beaver Creek near Newhalem	7	150	112	90	70	61	55	52
	30	210	150	116	85	72	63	58
	90	315	225	175	128	108	91	84
	183	400	320	265	205	176	152	140
Skagit River near Newhalem	7	1,200	930	750	590	520	460	430
	30	1,400	1,040	860	690	620	560	530
	90	2,050	1,470	1,200	930	820	730	680
	183	2,850	2,050	1,580	1,170	1,000	880	820
Ruby Creek below Panther Creek near Newhalem	7	200	126	94	72	64	59	57
	30	255	160	116	87	78	72	68
	90	335	250	195	138	110	88	80
	183	490	390	315	220	180	150	132
Thunder Creek near Newhalem	7	175	130	107	84	73	65	62
	30	260	165	122	94	85	80	76
	90	385	250	180	130	113	104	100
	183	485	390	320	245	210	190	180
Stetattle Creek near Newhalem	7	48	36	29	23	21	19	18
	30	93	57	40	30	26	24	23
	90	165	110	77	50	42	39	38
	183	210	160	132	102	90	79	74
Skagit River at Newhalem	7	3,900	2,700	1,950	1,400	1,200	1,100	1,020
	30	4,400	3,500	2,800	2,000	1,600	1,300	1,130
	90	5,100	4,200	3,500	2,550	2,100	1,750	1,600
	183	5,700	4,800	4,100	3,200	2,700	2,300	2,100
Skagit River above Alma Creek near Marblemount	7	4,000	3,100	2,500	1,850	1,550	1,300	1,170
	30	4,600	3,800	3,200	2,400	2,000	1,700	1,500
	90	5,200	4,600	4,100	3,400	3,000	2,700	2,500
	183	6,400	5,600	4,900	4,000	3,500	3,100	2,900
Bacon Creek near Marblemount	7	160	120	97	76	67	61	58
	30	270	170	122	91	80	74	72
	90	460	325	240	152	130	116	110
	183	580	470	390	290	255	235	225
Skagit River at Marblemount	7	4,800	3,550	2,850	2,200	2,000	1,800	1,700
	30	5,800	4,500	3,700	2,850	2,400	2,100	1,900
	90	6,800	5,600	4,700	3,600	3,000	2,500	2,150
	183	8,000	6,700	5,600	4,250	3,550	3,000	2,700
Cascade River at Marblemount	7	430	350	280	200	165	137	122
	30	620	460	350	240	190	155	138
	90	880	670	520	370	300	240	215
	183	1,100	920	780	620	530	460	420
Sauk River above White Chuck River	7	390	280	230	190	175	163	158
	30	520	370	300	245	220	200	190
	90	990	680	520	405	360	320	300
	183	1,370	1,100	890	670	570	490	440
Suiattle River near Mansford	7	800	700	620	510	450	390	360
	30	1,020	880	750	600	510	440	400
	90	1,430	1,160	990	820	730	670	630
	183	1,900	1,620	1,400	1,120	1,000	900	850
Sauk River near Sauk	7	1,800	1,550	1,300	1,010	860	730	660
	30	2,300	1,900	1,600	1,220	1,050	900	820
	90	3,450	2,850	2,450	1,960	1,700	1,500	1,400
	183	5,200	4,300	3,550	2,700	2,370	1,940	1,800
Baker River below Anderson Creek near Concrete	7	1,000	730	580	440	390	350	330
	30	1,400	920	690	500	440	390	360
	90	2,000	1,450	1,100	780	670	600	580
	183	2,500	2,100	1,700	1,300	1,100	990	920
Baker River at Concrete	7	1,300	970	770	580	500	440	405
	30	1,700	1,400	1,180	950	840	750	700
	90	2,500	2,050	1,700	1,370	1,200	1,050	980
	183	3,050	2,600	2,200	1,840	1,650	1,490	1,400
Skagit River near Concrete	7	9,300	7,600	6,500	5,300	4,700	4,200	3,900
	30	10,700	9,000	7,800	6,300	5,500	4,900	4,600
	90	14,500	11,700	9,900	8,000	7,200	6,600	6,300
	183	18,800	15,300	13,000	10,500	9,400	8,500	8,000

TABLE 21.—Continued

Gaging station	Number of consecutive days	Streamflow in cfs, for indicated recurrence, intervals, in years						
		1.05	1.30	2.0	5	10	20	30
Finney Creek near Concrete	7	46	32	24.5	17	13.5	11	10
	30	66	45	33	21	16.2	13	11
	90	152	98	65	37	26	18.5	15
	183	350	225	165	115	96	81	75
Alder Creek near Hamilton	7	12.8	10.5	9.0	7.0	6.1	5.4	5.0
	30	14.2	11.7	9.7	7.6	6.6	5.8	5.4
	90	16	13.5	11.4	9.0	7.7	6.7	6.2
	183	26.5	21	17	12.8	10.7	9.0	8.2
Day Creek near Lyman	7	35	26	19.5	13	10.2	8.0	7.0
	30	52	36	26	16	12	9.1	7.8
	90	130	84	55	30	20.5	14	11.6
	183	260	185	135	88	74	65	62
East Fork Nookachamps Creek near Clear Lake	7	4.8	3.3	2.3	1.4	1.0	.8	.6
	30	9.1	5.7	3.7	2.0	1.4	1.0	.8
	90	45	24	13	5.3	3.0	1.7	1.3
	183	115	66	42	23.5	18.5	16	14.8
Skagit River near Mount Vernon	7	10,100	8,400	7,200	5,800	5,100	4,600	4,300
	30	11,700	9,700	8,300	6,700	5,800	5,200	4,900
	90	15,000	12,200	10,500	8,500	7,700	7,000	6,600
	183	20,000	16,800	14,200	11,600	10,100	9,000	8,300
Friday Creek near Burlington	7	4.2	3.1	2.4	1.7	1.4	1.2	1.1
	30	6.2	4.1	2.9	2.0	1.6	1.3	1.2
	90	16.5	7.5	4.4	2.6	2.0	1.6	1.4
	183	44	28	17	9.4	6.2	4.2	3.3
Samish River near Burlington	7	37	30	26	21.5	19.5	17.8	16.8
	30	47	35	29	24	21	19	18
	90	77	51	37	27	23	20	19
	183	137	106	83	57	46	37	33

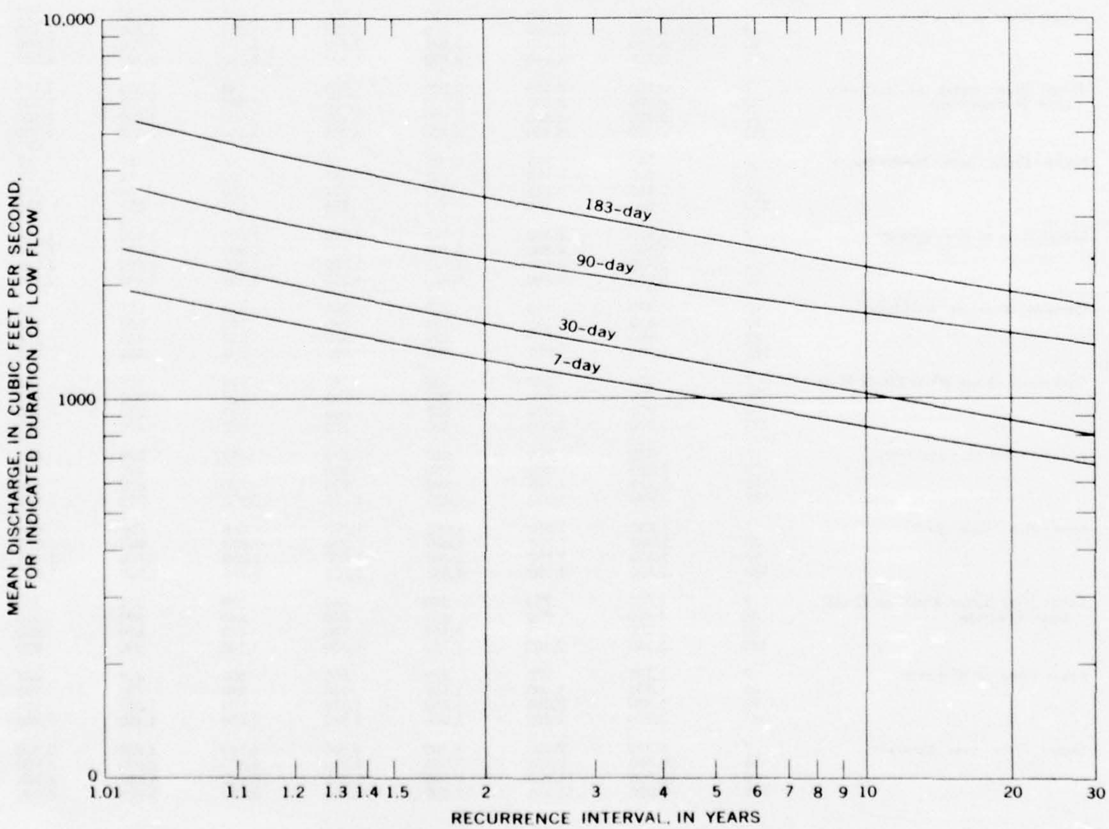


FIGURE 42.—Low-flow frequency, Sauk River near Sauk, 1946-63.

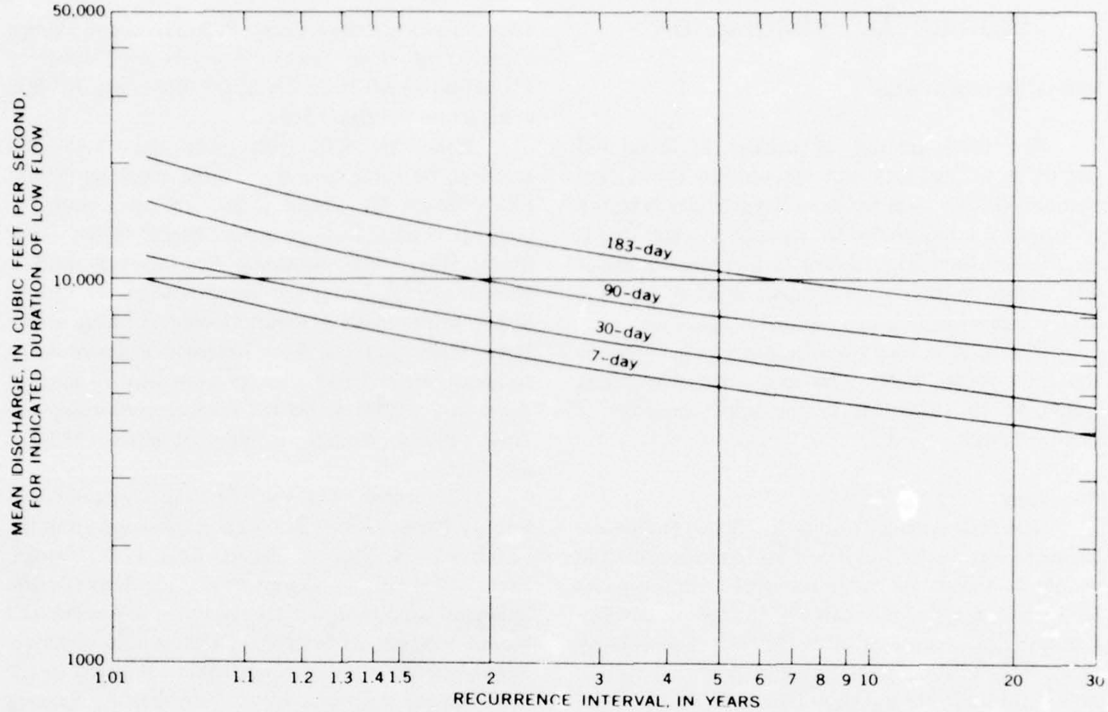


FIGURE 43.—Low-flow frequency, Skagit River near Concrete, 1946-63.

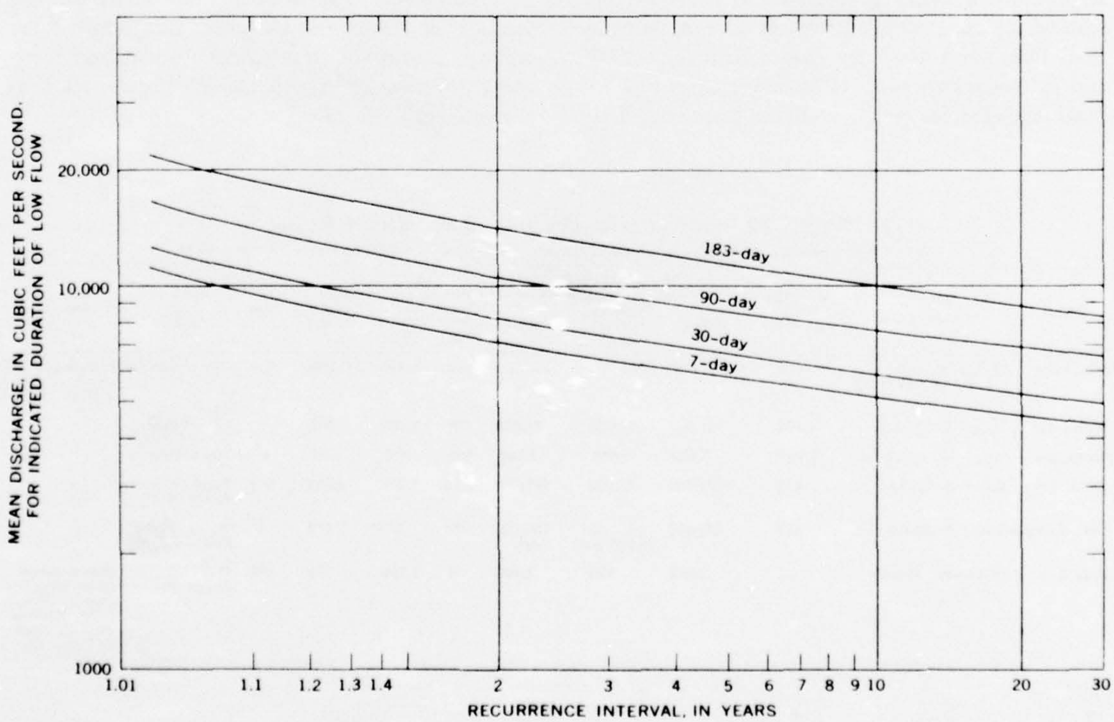


FIGURE 44.—Low-flow frequency, Skagit River near Mount Vernon, 1946-63.

STORAGE AND REGULATION

Natural Surface Storage

The total amount of storage in lakes and glaciers in the basins is not known, but the surface area covered by these water bodies provides at least a comparative indication of the amount of water that is stored. The total lake surface in the basins is about 40.5 square miles, only 9.1 square miles of which is natural, the remaining area represents reservoirs.

The total surface area of glaciers in the basins is about 63 square miles. The most extensive glacier system in the basins is in the upper drainage of Thunder Creek.

Reservoirs

The following discussion of existing and potential reservoirs in the Skagit-Samish Basins is restricted mainly to those over 5,000 acre-feet in size. Smaller reservoirs are included because of their importance to a project, or because of plans for their later enlargement. The existing reservoirs and potential storage sites in the basin are shown in Figure 45.

Existing reservoirs—Information on existing reservoirs in the basins is presented in Table 22. The flow of the upper Skagit River has been regulated by Ross Dam since 1940, by Diablo Dam since 1929, and by Gorge Dam since 1924. Baker River flow has been regulated for power at Baker Lake since 1959 and at Lake Shannon since 1925. The active storage capacity of these reservoirs totals approximately 1,120,000 acre-feet on the Skagit River and 363,000 acre-feet on the Baker River.

Ross Reservoir, with more than 1,434,000 acre-feet of total storage, has the most significant influence on the Skagit River. The dam probably controls one-third of the annual runoff to the upper Skagit River. The remaining two-thirds in uncontrolled, except for power regulation at the various power plants and for minor flood regulation at the Baker River projects. Ross Reservoir is drawn down to about one-half full capacity from January through April, and is filled during the flood season in May and June. Flood storage is approximately 120,000 acre-feet.

The primary phase of the Judy Project (Skagit County Public Utility District) diverts water from the watersheds of Turner, Mundt, East Fork, Nookachamps and Gilligan Creeks to provide domestic and industrial supplies to an area near Sedro Woolley and Mount Vernon. At present, storage is approximately 3,000 acre-feet, which is negligible compared to the total flow of the major rivers in the area. An increase to over 6,000 acre-feet of storage is planned.

Potential storage sites—Because of its size and location in the North Cascades, the Skagit River drainage provides a great potential for storage reservoirs. Information on potential storage sites, is presented in Table 23.

TABLE 22.—Existing reservoirs in the Skagit-Samish Basins

Use; F, flood control; P, Hydro-electric development; WS, municipal and industrial water supply.

Name	Location Stream, T-R-S	Drainage area (sq mi)	Storage (Acre-ft) Active	Storage (Acre-ft) Inactive and/or dead	Storage (Acre-ft) Total	Dam dimensions Ht (ft)	Dam dimensions Width (ft)	Reservoir area (acres)	Use	Applicant or owner	Remarks
Ross Lake	Skagit R. and Ruby Cr. 38-13-35	444	1,052,000	382,000	1,434,000	540	1,300	11,678	F, P	City of Seattle	Includes 120,000 acre-ft of flood-control storage.
Diablo Lake	Skagit R. 37-13-5	1,125	61,000	28,000	89,000	389	1,180	910	P	City of Seattle	
Gorge Res.	Skagit SR. 37-12-14	1,160	7,000	1,500	8,500	285	670	241	P	City of Seattle	
Baker Lake	Baker R. 37-9-31	215	221,000	77,000	298,000	115	1,200	4,985	F, P	Puget Sound Power & Light	
Lake Shannon	Baker R. 35-8-2	297	142,000	unknown 17,000 (est)	159,000 (est)	285	530	2,218	P	Puget Sound Power & Light	
Judy Res.	Offstream 35-5-33	--	3,000	100	3,100	51	1,200	108	WS	PUD #1 Skagit Co.	Stores diversions from Turner, Mundt, E. Fk. Nookachamps, and Gilligan Cr.

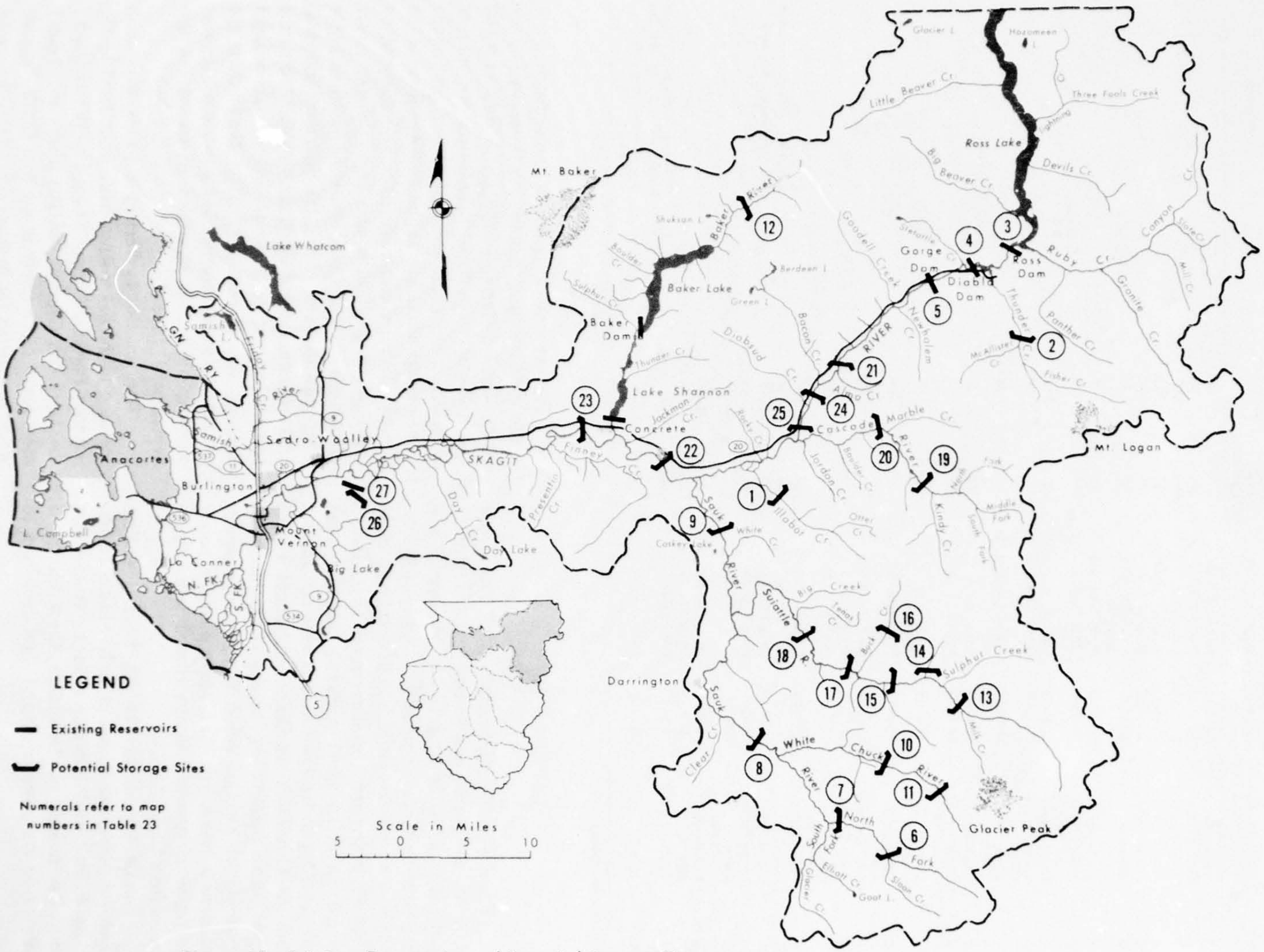


Figure 45. Existing Reservoirs and Potential Storage Sites in the Skagit—Samish Basins

TABLE 23.—Potential storage sites in the Skagit-Samish Basins

Map no.	Project name	T-R-S	River and mile	Total storage (1,000 acre-ft)	Drainage area (sq mi)	Remarks
1	Illabot Cr.	34-10-1	Illabot Cr. 5		32	
2	Thunder Cr.	36-13-12	Thunder Cr. 9	134	92	
3	Ross (add.)	38-13-35	Skagit 104	2,045	999	
4	Diablo (add.)	37-13-5	Skagit	[1]61	1,125	
5	Gorge (add.)	37-12-14	Skagit	[1]7	1,160	
6	Sloan Cr.	30-12-29	Sloan Cr. 0.75 Sauk R. 7	28	52	
7	N. F. Sauk	30-11-16	N. F. Sauk 2.1	34	77	
8	Upper Sauk (Dan Cr.)	31-10-9	Sauk R. 32	133	238	
9	Lower Sauk	34-10-19	Sauk R. 6	695	714	
10	Lower White Chuck	31-12-29	White Chuck R. 11	--	50	
11	Upper White Chuck	31-12-36	White Chuck R. 15	--	30	
12	Sulphide Cr.	38-10-17	Baker R. 28	115	60	
13	Upper Suiattle	32-13-32	Suiattle R. 32	--	98	
14	Downey Cr. #1A	32-12-14	Downey Cr. 6 Sulphur Cr. 3	--	49	
15	Downey Cr. #1	32-12-17	Suiattle R. 33	--	106	
16	Buck Cr. #1A	33-12-32	Buck Cr. 5	--	21	
17	Buck Cr. #1	32-11-14	Suiattle 28.5	--	182	
18	Lower Suiattle	33-11-31	Suiattle 21.5	--	256	
19	Hard-Kindy	35-12-34	Cascade R. 15.3	99.2	92	
20	Cascade	35-12-7	Cascade R. 8	96.7	144	Skagit Co. PUD #1 proposal
21	Copper Cr.	36-11-15	Skagit R. 86	150	1,270	City of Seattle proposal
22	Lower Faber	35-9-20	Skagit R. 62	1,500	2,400	
23	Dalles (54+mi)	35-8-16	Skagit R. 54	--	2,737	
24	Mile 74-81	36-11-32	Skagit R. 81	--	1,350	
25	Mile 78	36-11-21	Skagit R. 78	--	1,350	
26	Janicki Cr.	34-5-4	Offstream	4.5	--	Proposed addition to Judy Project PUD #1 Skagit Co.
27	Judy	35-5-33	Offstream	6	--	Enlargement of existing reservoir

[1] Additional storage

DIVERSIONS

From the city of Seattle's Ross Dam about 9,500 cfs. is diverted to a powerhouse and returned to the river a few hundred feet downstream. From the Diablo Dam, also operated by the city of Seattle, and about 4 miles downstream from Ross Dam, about 7,200 cfs. is diverted from the reservoir to the Diablo powerhouse under usual operating conditions and then returned to the river about 1 mile downstream from the dam. From the Gorge Dam, about 3 miles below Diablo powerhouse, the city of Seattle diverts 7,500 cfs. to generate power in the Gorge powerhouse near Newhalem. The water used for power generation is returned to the river 2 miles downstream from Gorge Dam.

Seattle also diverts 75 cfs. from Newhalem Creek for power generation at its Newhalem powerhouse. From a small crib dam about 1 mile upstream from the mouth of Newhalem Creek, water is diverted to the powerhouse and then discharged to Skagit River.

The upper Baker River dam immediately north of the Whatcom-Skagit County line is operated by the Puget Sound Power and Light Co. A total of 4,800 cfs. is diverted from Baker Lake for the operation of this plant. The powerhouse is an integral part of the dam, and the water is returned to Baker River at the damsite. Lower Baker River dam, also operated by the Puget Sound Power and Light Co. for power generation, is about 1 mile above the mouth of Baker River near Concrete. From the reservoir (known as Lake Shannon) about 6,000 cfs. was diverted to the powerhouse and returned to Baker River a short distance downstream until May 1965 when the powerhouse was destroyed. The powerhouse is under construction and is scheduled to go on the line September 1, 1968.

Two smaller hydroelectric plants have been operated in the Baker River basin since 1900 by the Superior Portland Cement Co. and more recently by the Lone Star Cememt Co. The plants are about 5 miles north of Concrete in the Bear Creek drainage. Water is diverted for hydroelectric power generation

use from Sulphur and Rocky Creeks. The entire flow of Sulphur Creek is often diverted to Rocky Creek and the combined flow of both creeks is, in turn, diverted to a reservoir on the North Fork of Bear Creek. The pipeline leading from this reservoir to Plant No. 1 is capable of delivering flows up to 65 cfs. The discharge from this plant passes into a reservoir on the main stem of Bear Creek about half a mile above Lake Shannon. From this reservoir, flows of as much as 83 cfs. are diverted to Plant No. 2 near the shore of Lake Shannon. The diversions from both the North Fork and the main stem of Bear Creek are discharged into Lake Shannon.

As of 1967, Valumines, Inc. is developing a small plant which will involve a diversion of 7.33 cfs. from Midas Creek, a tributary of Boston Creek in the Cascade River watershed. The water diverted will be returned to the stream a few hundred feet downstream.

The Washington Department of Fisheries maintains two sizable diversions in the Skagit River basin for fish propagation purposes. The Skagit Salmon hatchery at Marblemount obtains up to 10 cfs. from Clark Creek and 15 cfs. from Jordan Creek. Both diversions are ultimately returned to Skagit River.

The Washington Department of Fisheries Samish River Salmon Hatchery, located on Friday Creek, diverts 20 cfs. from the creek which is returned below the hatchery ponds.

The Three Rivers Plywood and Timber Co. and Summit Timber Co. jointly divert 5 cfs. from the Sauk River near the town of Darrington to operate a millpond. The diversion bypasses a few hundred feet of the river. The Marona Mill Co. has a similar operation along the Sauk River about 2 miles north of Darrington. This pond utilizes diversions of 5 cfs. from the Sauk River and up to 5 cfs. from a small unnamed tributary in the Sauk River flood plain. Overflow from the pond is returned to the river by way of the unnamed stream channel.

The Skagit County Public Utility District No. 1 diverts water from the upper reaches of ten small streams that drain Cultus Mountain and operates an elaborate collection system from these sources to provide municipal and community water supplies for Mount Vernon, Burlington, Sedro Woolley, LaConnor, and adjacent areas. The PUD holds rights to 4 cfs. from two of these streams and maintains claims to vested rights from nearly all of the streams for a total of about 10.4 cfs. The diverted waters are collected in Judy reservoir, a storage facility for the distribution system. None of the diversions are returned to their respective stream systems.

The city of Anacortes diverts 3.5 cfs. from the lower Skagit River for municipal supply about 1 mile northwest of Mount Vernon. None of the water is returned to the river.

In 1965, about 3,000 acre-feet of water was diverted for irrigation in the Skagit River basin, principally in the lower part of the basin.

QUALITY OF SURFACE WATER

Chemical and Sanitary Quality

Chemical quality of surface water in the Skagit-Samish Basins is excellent, and the water is acceptable for practically all uses.

Chemical quality data are available for two sites on the Skagit River and for one site on the Samish River. Monthly samples were collected for 5 years at each site (Table 58). At the Marblemount site on the Skagit River, dissolved-solids content ranged from 23 to 44 ppm, and values of hardness ranged from 14 to 30 ppm. Mineralization of the Skagit River water increases only slightly downstream. Near Mount Vernon, the dissolved-solids content ranged from 22 to 52 ppm, and hardness values ranged from 15 to 32 ppm. The Samish River is only slightly more mineralized than the Skagit River. Maximum measured dissolved-solids content and hardness for this river are 71 and 44 ppm, respectively.

Turbidity of the Skagit River increases from Marblemount to Mount Vernon because of changes in land use. Turbidity in the lower Samish River is comparable to that of the lower Skagit (Table 58).

In general, the sanitary quality of surface water resources in the Skagit-Samish Basins is satisfactory except in areas near population centers in the lowlands. The MPN value of coliform organisms in the Skagit River at Marblemount is generally less than 50. This very low MPN is typical of a stream draining remote mountain areas. Higher MPN values occur in reaches downstream from Marblemount, as a result of domestic and livestock wastes associated with greater population density. In the Skagit River near Mount Vernon, the coliform bacteria count has ranged from 0 to 24,000 MPN.

Water samples collected from the Samish River near Burlington generally showed coliform MPN values ranging from 23 to 930; however, one sample had an MPN value of 11,000.

Stream Temperatures

Of the four stations from which temperature data were obtained in the Skagit-Samish Basins, thermographs have been operated at three (Table 59). The summer temperatures recorded in the Samish River near Burlington are the highest in the basins. This stream heads in the coastal hills near Wickersham, and hence, is not subject to the cooling influence of snowmelt.

Water flowing past the sampling point on the Cascade River at Marblemount is near freezing in the winter, while that flowing past the two sampling points on the main stem Skagit River is not. This difference, amounting to as much as 6°, may be an effect of reservoir regulation. The consistently lower summer temperatures of the flow in the Skagit River—3 to 6° lower than those in the Samish River—probably are a result of the same effect.

Sediment Transport

In the upper drainage of the Skagit River basin, upstream from Concrete, the terrain is mountainous and much of the land is rough, broken, and rocky. Fairly smooth hills and low mountain spurs at the lower elevations are mantled with glacial debris that is not easily eroded when undisturbed by man. The flood plains contain well drained alluvial soils underlain by coarse-textured materials. Although precipitation is abundant, excessive erosion on the flood plains is prevented by heavy vegetative cover. When the area is subjected to logging and accompanying construction, fine sediments are commonly removed by erosion during periods of intense precipitation. Channel erosion is quite variable; it is restricted mostly to wide sections of the stream valleys and as evidenced by many gravel and cobble bars.

Much of the fluvial sediment in the upper Skagit basin is derived from glaciers. Glacial streams that transport large quantities of sediment include the Cascade, White Chuck, and Suiattle Rivers. The highest sediment concentrations in these rivers occur during warm periods, when large volumes of glacial melt water are flowing.

Reservoirs tend to reduce sediment concentrations; much of the sediment in the Baker River, for instance, is deposited in Lake Shannon. Much of the eroded sediments in the upper Skagit River basin are trapped in Ross Lake.

In the lower Skagit basin, downstream from Concrete, alluvial soils on flood plains vary from poorly drained to well drained. The well drained soils are underlain by coarse-textured materials. The flood plain soils, similar to those in the upper drainages, are easily eroded during periods of intense precipitation, except in areas of heavy vegetation. Removal of vegetation for construction or farming results in sheet and rill erosion of fine sediments. Many of the tributary streams in the lower basin drain foothills and low mountains. These tributaries have sediment transport characteristics similar to those of nonglacial mountain streams; they generally contain little sediment except during periods of high runoff.

Analysis of data obtained in 1965 and 1966 indicates that the Skagit River can be expected to transport a sediment load of about 10-million tons during a year of normal streamflow. When the river discharge is about 70,000 cfs, a daily suspended sediment load of about 640,000 tons can be expected. Observed concentrations of suspended sediments in the Skagit River near Mount Vernon ranged from 19 to 654 ppm during 1965-66.

The Samish River is a small stream that heads in low mountains south of Bellingham and flows over an alluvial and glacial plain into Samish Bay. The terrain in the headwaters is rough, and rock outcrops, boulders, and cobbles are prominent. At lower elevations, the terrain consists of fairly smooth hills mantled with glacial debris. Alluvial soils on the flood plain are easily eroded during intense precipitation, especially where the vegetative cover has been removed. Channel erosion is evident along much of the Samish River.

Analysis of samples obtained during 1965 and 1966 indicates that a total sediment load of about 10,000 tons may be transported in the Samish River during a year of normal streamflow. When the flow near Burlington is 5,000 cfs (this discharge has a 12-year recurrence interval), a daily suspended sediment load of about 4,000 tons can be expected. Observed concentrations of suspended sediment ranged from 6 to 60 ppm during 1965 and 1966.

The most serious sediment problems in the Skagit-Samish basins can be attributed to natural glacier erosion from the vicinity of Glacier Peak.

Because of sediment deposition in the lower Skagit River, navigation is limited to small boats with shallow draft. River improvements consist primarily of training dikes, removal of snags, and small amounts of dredging. If a deep-water channel were to be maintained, deposition of sediment in the lower river would be a greater problem than now.

GROUND WATER

Significant differences in ground water conditions exist between lowlands and mountains in the Skagit-Samish Basins, owing to contrasting geologic environment. The lowlands are generally west and north of Cultus Mountain, and the mountains are to the east.

LOWLANDS

Geology and Ground Water Occurrence

The important aquifers in the lowlands are contained in coarse Quaternary deposits which are rather continuous over a 250 square mile area. Thicknesses of the Quaternary sediments exceed 500 feet in localized areas. The sediments become thinner toward northern and southern boundaries of the basins, and toward the mountains where they lap onto older consolidated rocks. On outlying islands, Quaternary sediments are generally thin or absent.

Quaternary deposits exposed at the surface are principally alluvium, till, and recessional outwash. Alluvial deposits occur on the broad deltas and flood plains of the Skagit and Samish Rivers. Near the shoreline the alluvium is generally fine grained and contains saline water. Inland and in contrast, alluvial sand and gravel containing fresh water become more abundant and increase in thickness. Nearly everywhere it occurs, alluvium is saturated to within a few feet of the land surface.

A prominent till-capped upland occupies much of the area between Burlington and Padilla Bay. Till and outwash cover the land areas east of Mount Vernon, north of Sedro Woolley, and south of the Skagit River tideflats. The presence of outwash beneath the alluvium, and the occurrence and water-bearing properties of subtill deposits, have not been established.

Limited information indicates that the more productive lowland aquifers are contained in the coarser alluvial deposits beneath the Skagit and Samish flood plains. However, outwash deposits also may contain high-yielding aquifers locally.

Virtually all recharge to the lowland aquifers is by infiltration of precipitation. Due to fineness of river-bed sediments, significant recharge from the Skagit and Samish Rivers is doubtful. Aquifers in the lowlands are estimated conservatively to receive an average of about 50,000 acre-feet of recharge annually.

The natural discharge of ground-water is mostly into the Skagit and Samish Rivers and their tributaries. However, considerable amounts are lost to the atmosphere through evaporation and transpiration on the low-lying deltas where the water table is at or very near the land surface. Increased pumping of ground water in flood-plain areas could slavage much of the natural discharge, and might provide some land-drainage benefits.

Quality of Ground Water

Ground water in the lowlands is suitable for irrigation and many domestic purposes, but the objectionable amounts of iron and excessive hardness commonly reported by well owners indicate that industrial uses may be limited. Ground water increases in salinity toward the bay areas, but significant encroachment of saline water has not as yet been detected.

Utilization and Development

Groundwater pumped in the lowlands is used mostly for domestic purposes. Most of the public-supply systems depend on ground-water sources. Irrigation using ground water occurs principally in a small area west of Mount Vernon. Most of the water pumped for all purposes is from alluvial aquifers in the flood plain and delta areas of the Skagit River.

Figure 23 shows order-of-magnitude estimates of expected well yields in the study area. Due to the complexity of subsurface deposit, however, yields locally can be much greater or much less than shown on the map. For example, water-well information at Burlington indicates that 600 gpm can be obtained from 12 feet of water-bearing sand and gravel. Flowing artesian wells may be produced by tapping deeper aquifers in the deltas and some of the low-lying areas adjacent to shorelines.

Satisfactory ground-water supplies are difficult to obtain at some places on the offshore islands, and near shoreline margins of the deltas. Where Quaternary sand and gravel outwash occurs on islands, yields of 10 to 50 gpm can often be obtained at depths of 100 feet or less, but where these Quaternary deposits are absent, wells produce less than 10 gpm from aquifers in consolidated rock. Near the delta shorelines, the predominance of fine-grained materials in many places makes adequate ground-water supplies difficult to obtain, and any water that is produced may be highly mineralized.

MOUNTAINS

In the mountains, east of Cultus Mountain, gravel and sand aquifers occur in Quaternary outwash and alluvium. These deposits locally are at least 200 feet thick, and occupy about 300 square miles in broad valleys of the Skagit River and its major tributaries. The abundance of precipitation suggests that these aquifers could receive a relatively large recharge. Depths to water in shallow aquifers are usually less than 20 feet. Some deeper aquifers are confined under artesian pressure below till or clay, and wells that tap these aquifers may flow.

Chemical quality of ground water is generally excellent and the water is suitable for practically all uses, although objectionable concentrations of iron are reported in a few wells less than 30 feet deep.

Most wells in the mountains are used principally for domestic purposes and are 50 feet deep or less. A few wells, mainly those used for irrigation, yeild more than 500 gpm.

In areas where Quaternary sediments are absent, ground water is obtainable only from consolidated rocks in which well yields of only 10 gpm or less can be expected.

STILLAGUAMISH BASIN

SURFACE WATER

The Stillaguamish Basin has an area of 690 square miles, including 6 square miles of salt water. A map of the basin is shown in Figure 55. The Stillaguamish River, the only major stream in the study area, rises in the Cascade Mountains at elevations of 4,000 to 6,000 feet and drains an area of 684 square miles. The upper drainages are steep mountainous valleys containing turbulent streams and forested lands. The lower, or western, portion consists of an extensive delta plain, alluvial flats, low glacial outwash plains, and a few lateral or frontal moraines.

The main tributaries are the North and South Forks, which join near Arlington. From the confluence, the main stem flows for approximately 23 miles to Puget Sound. The North Fork heads above Darrington, where it emerges from its narrow valley at an altitude of 500 feet. It then meanders westerly approximately 30 miles in a wide valley to its confluence with the South Fork.

The South Fork heads above Silverton and falls more than 2,000 feet in 3 miles as it flows north from its source to the main valley at elevation 1,800 feet. Thence, it flows 26 miles through a gradually widening valley flanked by high mountains and ridges; in this reach, the river falls 1,000 feet to the head of Robe Canyon, and another 600 feet in 8 miles to the mouth of Canyon Creek, its principal tributary. Below Canyon Creek, the South Fork flows northwesterly through a canyon cut into glacial deposits, and enters a broader flood plain 4 miles above its confluence with the North Fork.

Below Arlington the river meanders through a broad, fertile flood plain to Puget Sound. Most of the river's flow enters the Sound through Hat Slough, the main outlet. During high stages, some flow also discharges through a small channel that divides into two distributaries known as South Pass and West Pass.

STREAMFLOW

Runoff Characteristics

Although the headwater tributaries of the Stillaguamish stream system do not extend to the crest of the Cascade Range, the upper reaches of the south Fork lie adjacent to the highly productive Sultan River basin, and, therefore, experience a similarly high runoff. Discharge from high altitude areas within the South Fork watershed probably averages about 140 inches annually and about 120 inches in the North Fork watershed. The Olympic Mountains orographic barrier exerts some influence on precipitation in the lowland area of the Stillaguamish Basin, so that mean annual runoff is reduced to less than 15 inches near the mouth. The unit runoff is about 7.1 cfs per square mile from the North Fork and 8.0 cfs per square mile for the South Fork. The average annual yield of the entire basin is estimated to be about 80 inches, or 2,900,000 acre-feet.

Fluctuations in annual runoff at one gaging site are shown on Figure 46. With few exceptions, trends are similar, but several differences are evident compared to the records of streams in adjacent basins.

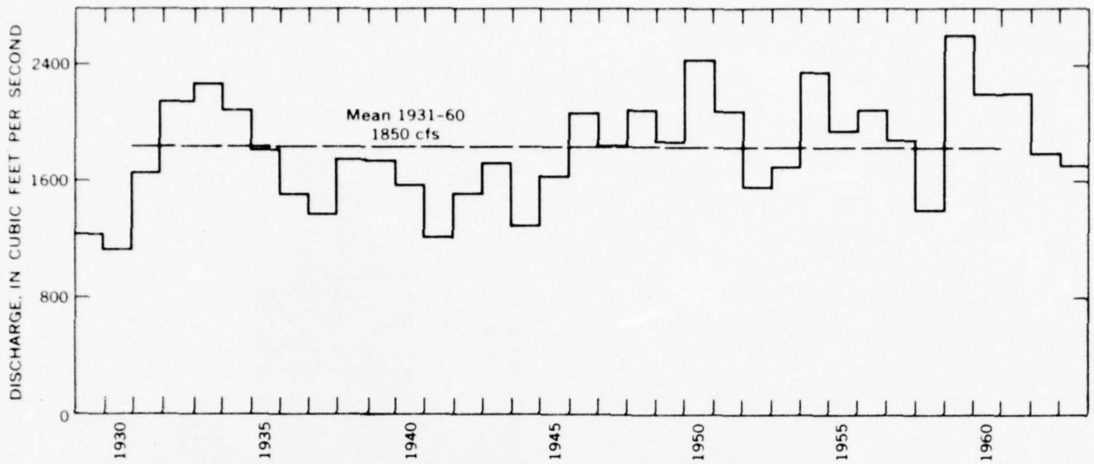


FIGURE 46.—Annual discharges, North Fork Stillaguamish River near Arlington.

During the period of record, the greatest runoff on the North Fork Stillaguamish River occurred in the 1959 water year when the discharge at the Arlington gage amounted to 141% of the 30 year mean. Minimum yearly flows were recorded in the 1930 water year when the yield of the North Fork was only 61% of the 30 year mean. The records display a 10 year period of below normal runoff from about 1936 to 1945; similar trends are shown by nearby streams

Seasonal runoff patterns for both forks of the Stillaguamish are quite similar. Both streams display winter and spring peak flows that are typical of rain and snow fed streams in western Washington. Because of a high percentage of low altitude area, the watersheds of both forks receive much of their precipitation as rain. This is reflected in Figures 47 and 48 by the higher winter peaks resulting from direct runoff. Snow storage at higher altitudes is sufficient to produce a moderate spring runoff peak in each fork. This factor is more significant in the South Fork drainage, however, where a greater percentage of the catchment area lies at high altitude.

Stream gaging stations on the lower reaches of the North and South Forks measure runoff from approximately 75% of the Stillaguamish Basin. Average annual discharge below the confluence of the forks is approximately 3,500 cfs.

Streamflow usually begins to increase in September or October from the summer base flow. Runoff generally decreases from December through March as a result of colder weather. As temperatures begin rising in April, snowmelt causes small increases in streamflow which reach a maximum following the snowmelt peak, usually by the end of May. Streamflow recedes to minimum base flow as snowpacks are depleted, usually by the end of August. At this time, discharge is sustained largely by ground water. Only six small glaciers exist in the basin, and these contribute little to summer low flows.

The variability of daily flow of streams in the Stillaguamish Basin is presented as flow duration data for selected gaging stations in Table 24.

Flood Characteristics

Floods caused by high rainfall with accompanying snowmelt are shown by characteristically sharp rises on a hydrograph, followed by recessions almost as rapid. Two or more peaks often occur within 2 weeks. The maximum recorded discharges, which occurred on February 9, 1951, were 30,600 cfs on the North Fork and 27,000 cfs on the South Fork. The corresponding peak flow in the main stem of the Stillaguamish River near Arlington was estimated to be about 64,000 cfs.

Flood frequency curves of discharges of North and South Forks of the Stillaguamish River are presented in Figures 49 and 50. The periods of record are 1919-64 for the North Fork gage, and 1937-57 for the South Fork. Frequency statistics were extended to an equivalent record of 44 years for the North Fork and to 35 years for the South Fork by correlation with data from the South Fork Skykomish River near Index. which has a record period of 54 years.

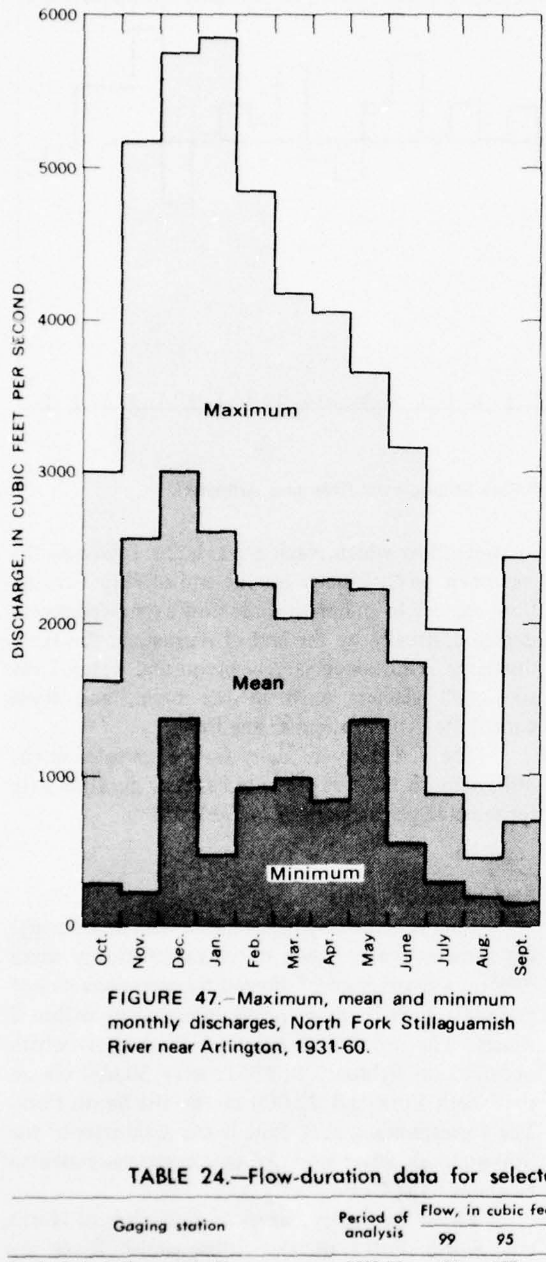


FIGURE 47.–Maximum, mean and minimum monthly discharges, North Fork Stillaguamish River near Arlington, 1931-60.

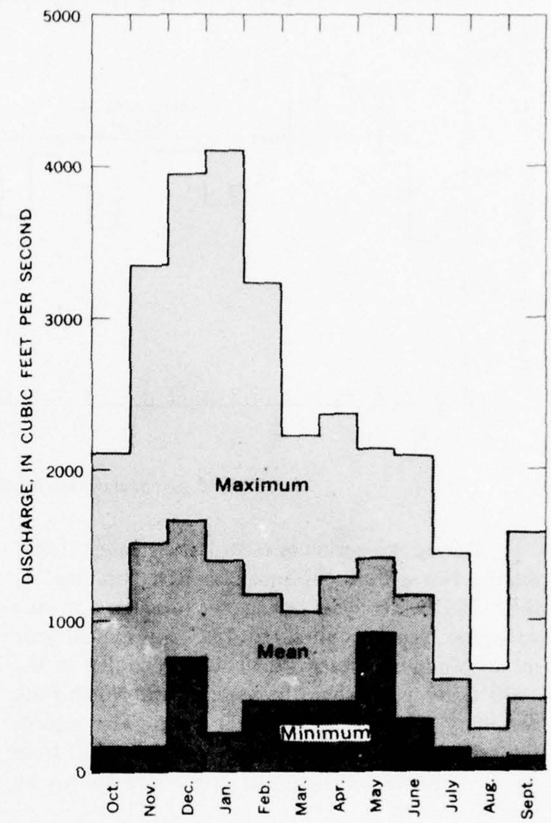


FIGURE 48.–Maximum, mean and minimum monthly discharges, South Fork Stillaguamish River near Granite Falls, 1931-60.

TABLE 24.—Flow-duration data for selected gaging stations in the Stillaguamish Basin

Gaging station	Period of analysis	Flow, in cubic feet per second, which was equaled or exceeded for indicated percent of time											
		99	95	90	80	70	50	30	20	10	5	1	0.1
South Fork Stillaguamish River near Granite Falls	1929-65	85	127	180	300	430	730	1,150	1,500	2,150	3,050	6,200	13,300
South Fork Stillaguamish River above Jim Creek near Arlington	1937-57	130	180	250	470	700	1,150	1,780	2,300	3,250	4,500	8,800	17,600
Jim Creek near Arlington	1938-56	8.4	13	19	40	77	146	234	308	460	640	1,100	2,000
Squire Creek near Darrington	1951-64	15.5	28	40	65	89	137	200	250	350	490	1,150	2,600
North Fork Stillaguamish River near Darrington	1951-57	38	62	92	160	250	430	660	840	1,200	1,680	3,350	8,000
North Fork Stillaguamish River near Arlington	1929-65	185	260	330	530	810	1,350	2,070	2,650	3,650	5,000	9,900	19,000
Pilchuck Creek near Bryant	1930-31, 1951, 1953-65	1.4	4.5	9.0	30	75	173	310	435	670	970	1,850	3,000

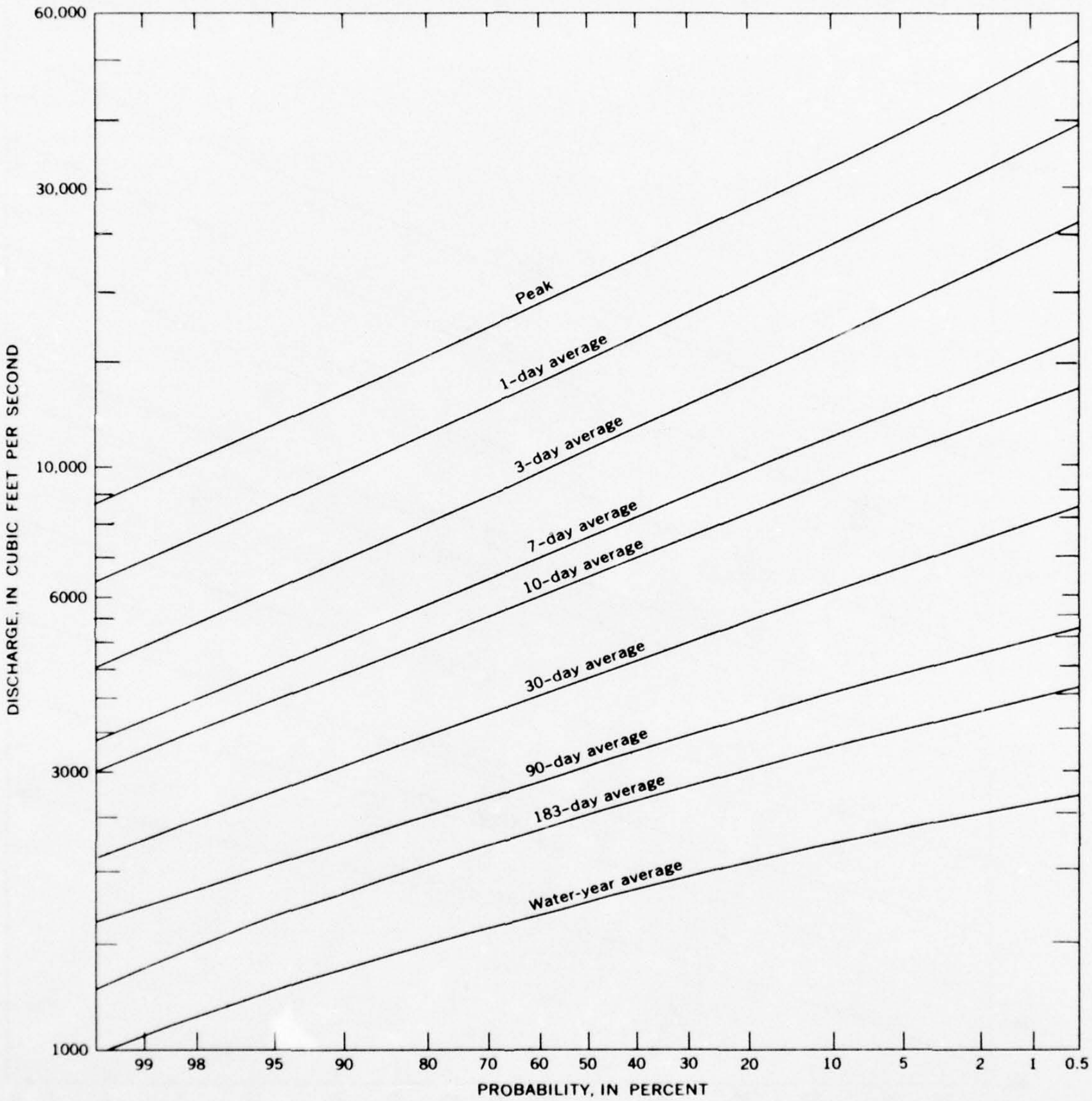


FIGURE 49.—Probability curves of annual maximum flows for specified time periods, North Fork Stillaguamish River near Arlington.

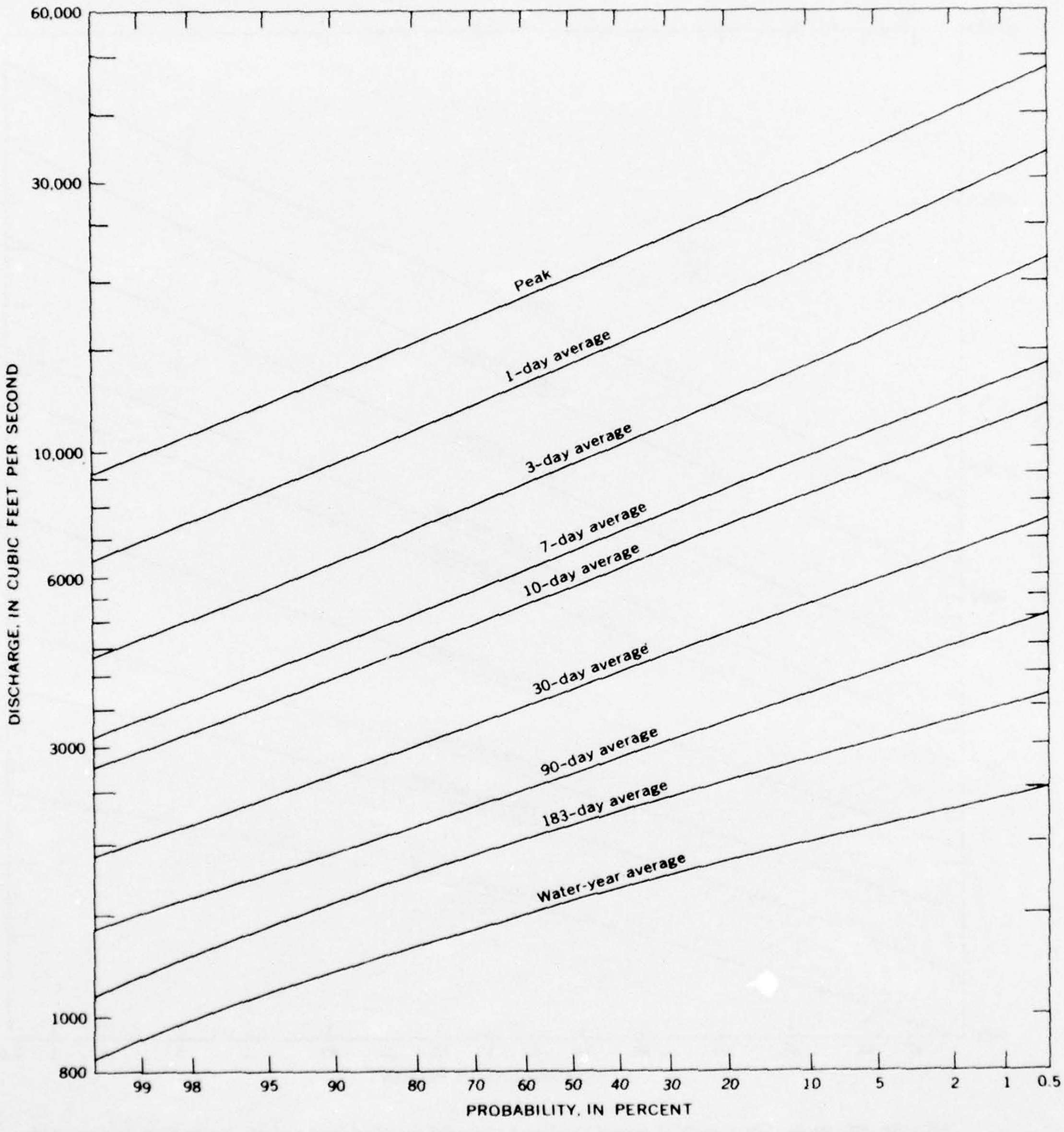


FIGURE 50.—Probability curves of annual maximum flows for specified time periods, South Fork Stillaguamish River above Jim Creek near Arlington.

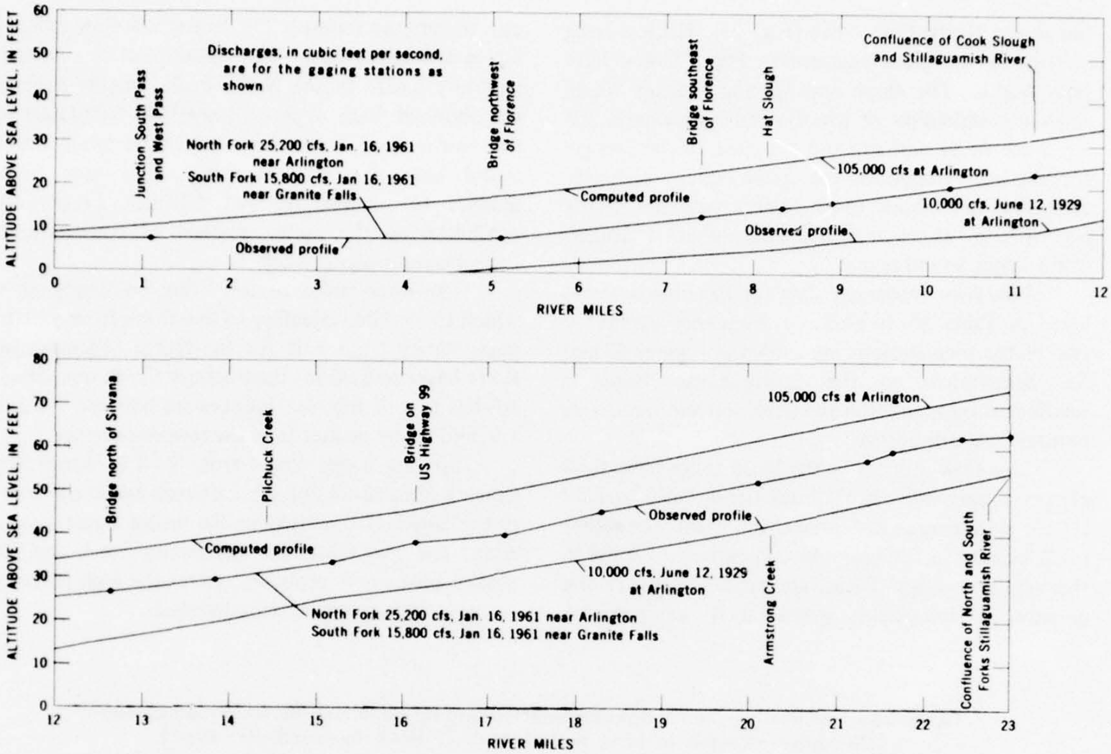


FIGURE 51.—Water-surface profile of Stillaguamish River, mile 0-23.

The ability of a stream to transport large quantities of water without causing damage depends on channel characteristics. These features can be shown in part by a graphical representation of the stream's water surface profile for various rates of discharge.

Profiles for the Stillaguamish River, shown in Figure 51, were plotted from observed or computed data. Values of velocity are not available. The observed profile for January 16, 1961, approximates the profile for bankfull condition. The Stillaguamish River has no abrupt changes in gradient between the mouth and river mile 23.

Low-flow Characteristics

Low-flow characteristics of streams in the Stillaguamish Basin are compared using indexes from low-flow frequency curves at nine gaging stations (Table 25). The indexes indicate that the low-flow yields are good in the South Fork basin and are only

TABLE 25.—Low-flow characteristics for selected gaging stations in Stillaguamish Basin

Gaging station	Drainage area (sq mi)	Low-flow index	Slope index	Spacing index
South Fork Stillaguamish River near Granite Falls	119	1.22	1.75	5.24
South Fork Stillaguamish River above Jim Creek near Arlington	199	1.08	1.89	5.30
Jim Creek near Arlington	46.2	.32	1.75	6.27
Squire Creek near Darrington, Wash.	20.0	1.30	2.38	5.49
North Fork Stillaguamish River near Darrington	82.2	.78	1.89	5.55
North Fork Stillaguamish River near Arlington	262	1.11	1.61	4.38
Armstrong Creek near Arlington	7.33	.16	1.69	2.12
Pilchuck Creek near Bryant	52.0	.10	5.00	22.2
Fish Creek near Arlington	7.52	.11	1.96	2.41

fair in the North Fork basin (Fig. 22). The low-lying streams in the areas adjacent to Puget Sound have poor yields. The slope and spacing indexes which show the variability of low flows of streams in the basin are fairly uniform and are close to the average for streams throughout the study region. The only exception is Pilchuck Creek, where variation in low flow is large—as much as twice that of other streams in the Puget Sound region.

Low-flow frequency data for the nine sites are listed in Table 26. In addition, frequency curves for two of the nine stations are shown in Figures 52 and 53. Streamflow in the Stillaguamish Basin is unaffected by regulation and diversion and represents natural flow conditions.

Low-flow indexes in the basin range from 0.10 cfs per square mile, in Pilchuck Creek basin to 1.30 cfs per square mile, in Squire Creek basin. The rather small indexes in the basin, in comparison to those in the adjacent Skagit Basin, are probably due to the absence of appreciable glacial melt water during critical summer months. The largest low-flow indexes are in the upper South Fork basin and in southern tributary basins to the North Fork. Smaller indexes are obtained from upper and northern tributaries of the North Fork basin. Lowland basins along Puget sound have the smallest values. The very small indexes for Armstrong and Pilchuck Creeks are attributed to the minor amount of contributions from ground water storage.

The slope index of the 7-day frequency curve which shows the variability of low-flows from year to year, ranges from 1.61 for the North Stillaguamish River basin to 5.00 for the Pilchuck Creek watershed. All but two of the nine indexes are between 1.6 and 1.9, and all are greater than the regional average.

Spacing index ranges from 2.12 in Armstrong Creek basin to 22.2 in Pilchuck Creek basin; the latter is the highest computed in the entire Puget Sound Area. The low values for Armstrong Creek and for nearby Fish Creek probably reflect the high porosity of the alluvial sediments in watersheds.

TABLE 26.—Low-flow frequency data for selected gaging stations in the Stillaguamish Basin
[Discharge adjusted to base period April 1, 1946, to March 31, 1964]

Gaging station	Number of consecutive days	Streamflow, in CFS, for indicated recurrence intervals, in years						
		1.05	1.30	2.0	5	10	20	30
South Fork Stillaguamish River near Granite Falls	7	240	180	145	110	94	82	75
	30	380	270	200	140	112	94	84
	90	800	540	390	260	205	165	147
	183	1,250	960	760	550	440	360	325
South Fork Stillaguamish River above Jim Creek near Arlington	7	400	280	215	154	130	113	105
	30	620	420	300	204	163	135	120
	90	1,300	820	550	350	290	260	250
	183	1,800	1,400	1,140	830	680	560	500
Jim Creek near Arlington	7	35	21	15	11	9.5	8.6	8.2
	30	53	30	20	13.2	11	9.6	9.0
	90	115	60	38	25	21	18	17
	183	170	120	94	67	54	46	41
Squire Creek near Darrington	7	44	34	26	17.5	13.7	10.8	9.4
	30	70	53	40	26	20	16	14
	90	180	120	79	45	34.5	28	25
	183	220	170	140	99	80	65	58
North Fork Stillaguamish River near Darrington	7	150	91	64	45	38	33	30
	30	180	116	82	56	46	38	35
	90	300	220	162	108	83	65	56
	183	600	460	355	240	185	148	130
North Fork Stillaguamish River near Arlington	7	580	390	290	225	200	180	173
	30	700	490	375	280	240	215	200
	90	1,300	890	630	410	350	310	300
	183	2,100	1,600	1,270	890	700	570	510
Armstrong Creek near Arlington	7	5.1	4.1	3.4	2.6	2.3	2.0	1.9
	30	5.9	4.6	3.8	3.0	2.7	2.5	2.4
	90	8.0	5.7	4.5	3.6	3.4	3.2	3.1
	183	13.4	9.3	7.2	5.8	5.3	4.9	4.7
Pilchuck Creek near Bryant	7	23	11	5.4	2.4	1.6	1.1	.9
	30	38	19	9.8	3.8	2.1	1.3	1.0
	90	125	67	36	13.5	7.1	3.9	2.7
	183	240	170	120	74	58	48	44
Fish Creek near Arlington	7	11.5	9.5	7.9	5.9	4.9	4.0	3.6
	30	13	11	9.1	7.0	5.8	4.9	4.4
	90	18.5	14	11	8.6	7.4	6.6	6.1
	183	33	25	19	14	12	10.8	10

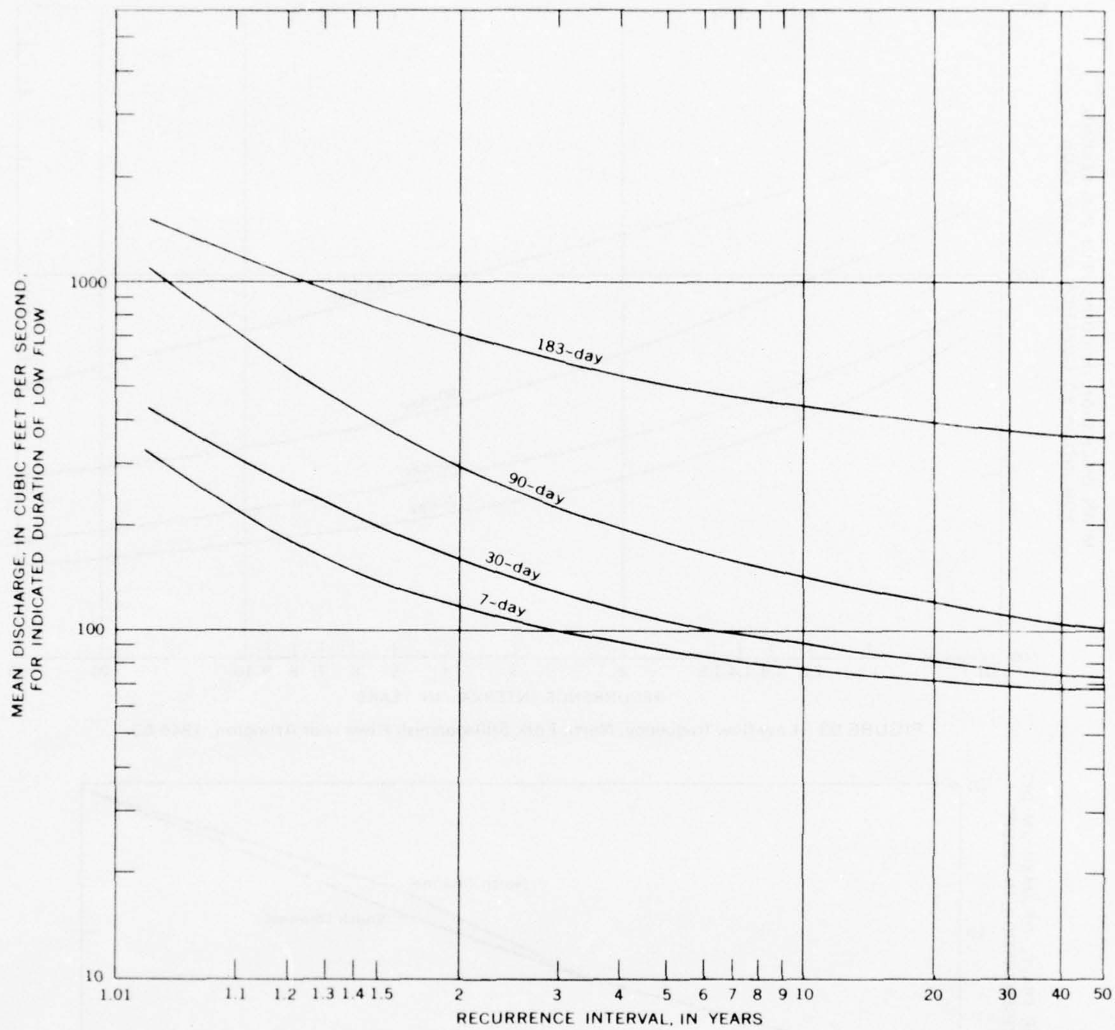


FIGURE 52.—Low-flow frequency, South Fork Stillaguamish River near Granite Falls, 1931-60.

Dispersion and Time of Travel

Using a fluorescent dye, rhodamine B, dispersion and time-of-travel studies for the Stillaguamish River were made for the reach between Arlington and Florence on August 24-25, 1966 by the Geological Survey. Profiles of discharge and of the travel time of maximum dye concentrations with respect to river miles are illustrated in Figure 54.

Discharge of the Stillaguamish River during this study was about 600 cfs. However, the flow decreased somewhat downstream. Near Silvana, about a 4 mile reach of the river divides into North Channel and South Slough. Discharges in these channels were 220 and 390 cfs, respectively.

The river also divides near Florence but practically all of the flow is through the river's south distributary, Hat Slough. Discharge fluctuations of unknown magnitude occurred near Florence owing to the tidal influence.

The measured travel speed of the peak concentration decreased with distance downstream. In the upper 6.4 mile reach the time of travel was 66 minutes per mile, and in the lower 8.6 mile reach it was 89 minutes per mile. Where the river divides near Silvana, movement of the dye cloud was more rapid

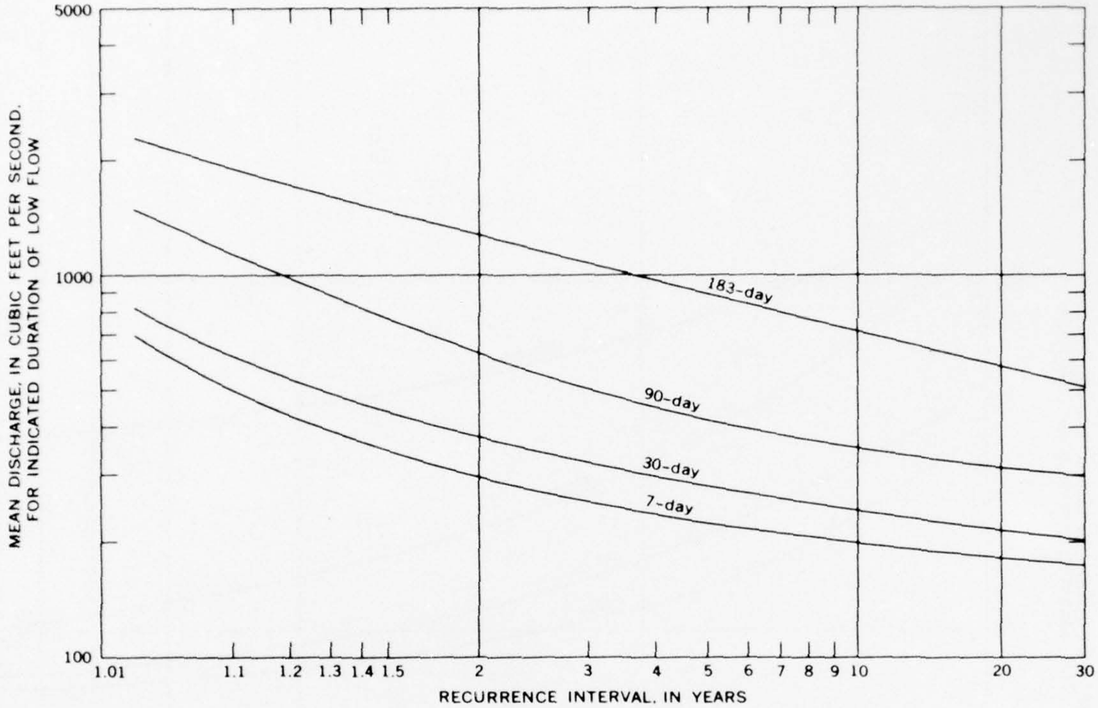


FIGURE 53.—Low-flow frequency, North Fork Stillaguamish River near Arlington, 1946-63.

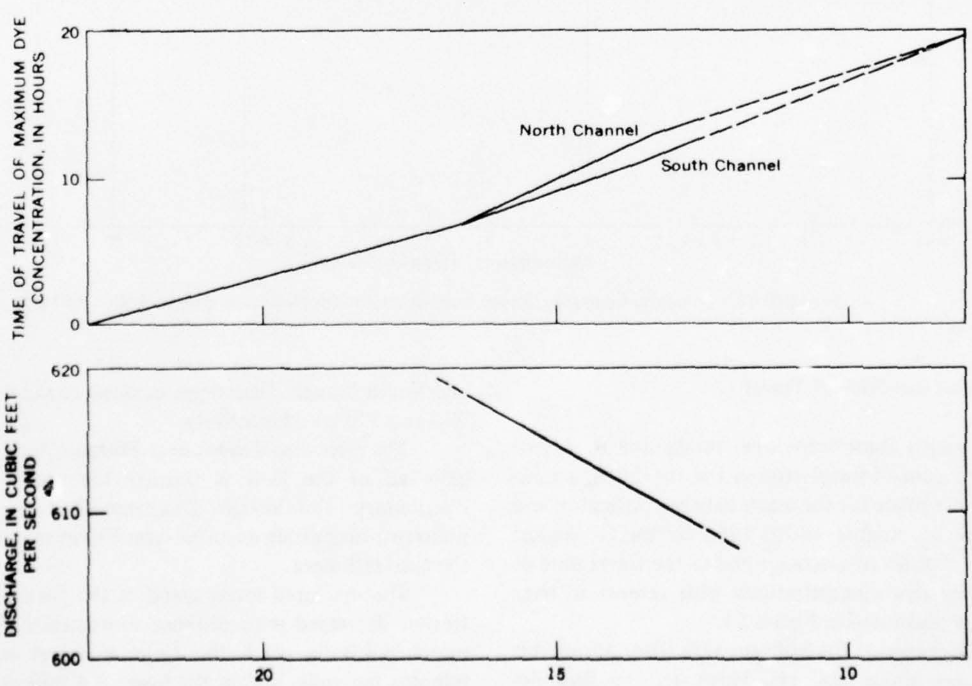


FIGURE 54.—Water discharge and time of travel of dye, Stillaguamish River, August 24-25, 1966.

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COMPREHENSIVE STUDY OF WATER AND RELATED LAND RESOURCES. PUGET --ETC(U)
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through South Slough than through North Channel. The average time of travel for the 15 mile reach via South Slough was 79 minutes per mile.

The dispersion coefficients obtained were rather uniform, and averaged about 200 square feet per second; dispersion apparently was least in the reach through North Channel near Sylvana.

STORAGE AND REGULATION

Natural Surface Storage

The total amount of storage in lakes and glaciers in the basin is not known, but the surface area covered by these water bodies provide at least a comparative indication of the amount of water that is stored.

The total lake surface area in the basin is about 2.8 square miles, most of which is accounted for by Lake Cavanaugh. The total surface area of glaciers in the basin is only about one-half of a square mile.

Reservoirs

The Stillaguamish River is as yet unregulated. Potential storage sites in the basin are primarily on the South Fork Stillaguamish River. The North Fork has only one site, at Oso. Information on major potential storage sites in the basin is presented in Table 27, and locations of the sites are shown in Figure 55.

DIVERSIONS

Of the many diversions in the Stillaguamish Basin, most are small; only two are 5 cfs or more. Near the headwaters of the North Fork of the Stillaguamish River, the State Department of Game diverts 5 cfs from a small tributary, called Whitehorse Mountain Springs. Nearly all the water is returned to the stream about 1,000 feet below the point of diversion. The State Department of Fisheries holds rights to 25 cfs to operate a fishway at Granite Falls on the South Fork of the Stillaguamish River. The fishway lies adjacent to the stream channel for several hundred feet.

An estimated 4,000 acre-feet of water was diverted for irrigation in the Stillaguamish watershed in 1965; most of the irrigation was in the lower part of the basin.

QUALITY OF SURFACE WATER

Chemical and Sanitary Quality

Chemical quality of surface water in the Stillaguamish Basin is excellent and the water is acceptable for practically all uses. Analyses of water samples collected monthly from the Stillaguamish River near Silvana show that dissolved solids content ranged from 17 to 58 ppm, and that the maximum hardness was 39 ppm during the period of record (Table 58). The North and South Forks and very similar chemically, and this quality changes only slightly from their confluence to the mouth of the Stillaguamish River. This dilute, soft water is typical of basins in western Washington where the water resources are largely undeveloped.

The sanitary quality of the surface waters of the Stillaguamish Basin is generally good. Undesirable coliform values occasionally occur below points of waste disposal, but the maximum MPN value observed, near Silvana, was only 1,500. The average MPN there was only 205 (Table 58). The coliform count for sampling points on the North Fork near Arlington averaged less than 200 MPN and the MPN value for

TABLE 27.—Potential storage sites in the Stillaguamish Basin

Map no.	Project name	T-R-S	River and mile	Proposed storage (1,000 acre-ft)	Drainage area (sq mi)	Use	Remarks
1	Oso	32-5-25	N. F. Stillaguamish 2.1	180	283		
2	Failey Mt. (Deer Cr.)	33-7-7 33-6-21	Deer Cr. and Cavanaugh L.	100	65 (75 total)		Diversion from Deer Cr. and storage in Cavanaugh Lake
3	Jorden	31-6-20	S. F. Stillaguamish 7.0	51	198		
4	Granite Falls	30-7-7	S. F. Stillaguamish 18.5	--	118		
5	Robe	30-7-2 30-7-12	S. F. Stillaguamish 24	198	147		
6	Tyree	30-8-14	S. F. Stillaguamish 31	100	90		
7	Silverton	30-9-22	S. F. Stillaguamish 45	180	43		

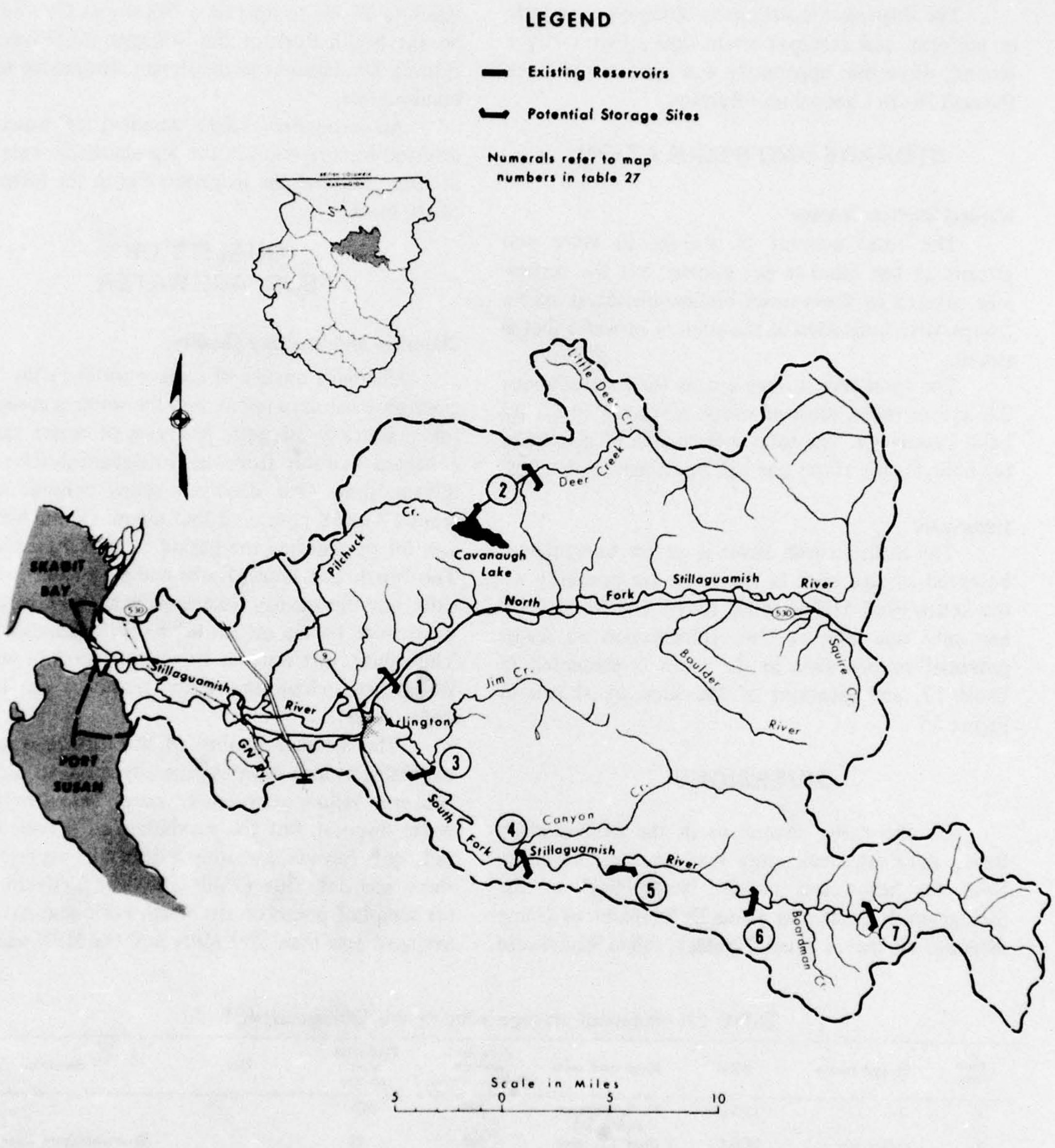


Figure 55. Existing Reservoirs and Potential Storage Sites in the Stillaguamish Basin

the South Fork near Granite Falls rarely exceeds 100. These data reflect a sanitary quality as good as that of any major stream on the east side of the Puget Sound study area.

Stream Temperatures

Records of stream temperature are available for four stations in the Stillaguamish Basin (Table 59). Thermographs have been in operation at two of the four sites. Summer water temperatures in Pilchuck Creek are the highest in the basin. The summer flow in this stream is very small providing ample opportunity for heating by solar radiation. The observed winter minimum temperatures in the North Fork Stillaguamish River are unusual in that they remain at least 3 to 4°F above freezing. The reason may be that the watershed does not extend to the crest of the Cascade Range, and therefore, occupies a lower and warmer terrain than most other major drainages in the area.

Sediment Transport

In the upper drainage, the forks of the Stillaguamish River flow through mountainous terrain in narrow valleys that contain alluvial and glacial deposits. Much of the land is rough, broken, and rocky. Only shallow soils have been formed, and in much of the area these soils are mixed or mantled with glacial material. The well-drained glacial till and outwash materials are not easily eroded, however, two major clay slides contribute to the sediment load of the Stillaguamish River, one on the North Fork near Halterman, and the other on the South Fork at Gold Basin. Leaching deposits from these two slides are causing heavy siltation and compaction of the river bed gravel downstream.

The upper drainage receives much precipitation, but heavy vegetative cover normally retards erosion. In areas subjected to logging and accompanying road construction, however, fine sediments are removed by sheet and rill erosion during intense rain. The movement of bed materials in the stream channels during high runoff is evidenced by large deposits of gravel and cobbles. During low flow, most streams in the upper drainage are nearly sediment free.

In the lower drainage, downstream from Arlington, the flood plains contain soils derived from alluvial deposits. Most soils in uplands of this area are underlain by loose glacial till and outwash and are well drained. Although precipitation is moderate, heavy vegetation normally prevents excessive erosion on steep slopes. Construction and farming in some parts of the lower drainage areas have nonetheless caused some increased sediment transport in streams. Some of the eroded sediments are deposited in numerous lakes and marshes, and therefore, do not enter the streams.

The streambed of the Stillaguamish River contains large amounts of sand and gravel that probably move as bedload during high runoff. Analysis of sediment samples obtained from the Stillaguamish River near Silvana in 1965 and 1966 indicates that the suspended sediment concentration is generally about 50 ppm. Erosion of streambanks is the most widespread significant problem.

GROUND WATER

Significant differences in ground water conditions exist between lowlands and mountains in the Stillaguamish Basin due to contrasting geologic environments. The lowlands are generally west of the foothills near Arlington, and the mountains are to the east.

LOWLANDS

Geology and Ground Water Occurrence

The important aquifers in the lowlands are in coarse Quaternary deposits, which are rather continuous over about 150 square miles. The Quaternary sediments may exceed 2,000 feet in thickness locally, but aquifers capable of furnishing large quantities of water to wells generally do not occur at depths greater than about 100 feet below sea level. Ground water can be obtained from depths less than 100 feet below land surface.

Quaternary sediments exposed at the surface are mostly till, recessional outwash, and alluvium. Plateaus in the lowlands, except in the Pilchuck Creek watershed and east of Arlington, are covered with till. Till is absent below most valley floors, except perhaps in an area near Arlington. Till is up to 100 feet thick on the higher uplands, and is truncated along some upland margins. Because it is composed largely of compacted fine materials, the till is not an important

aquifer, even though it is somewhat permeable.

The till-capped uplands west of Arlington cor tain isolated remnants of recessional outwash tha hold little water. The outwash is extensive on terrace north and east of Arlington and on the broad relic flood plain southwest of Arlington. Its presenc beneath the Stillaguamish flood plain has not beei established. Recessional outwash is composed predominantly of sand and gravel. Its maximum thickness is slightly greater that 150 feet on terraces north and west of Arlington, and is perhaps as much as 200 feet on the relict flood plain southwest of Arlington. In general, recessional outwash in the valleys is saturated to within about 10 feet of the land surface.

Deposits of recent alluvium, saturated to about river level, occur on the flood plain and delta of the Stillaguamish River. The alluvium consists mostly of sand, silt, clay, and peat, with minor amounts of gravel in localized areas. At the river mouth, the alluvium is probably more than 100 feet thick. Upstream, it becomes thinner and contains coarser materials.

Consolidated rocks that are older than Pleistocene and contain little water comprise much of the rugged upland areas north of the Stillaguamish River, principally in the Pilchuck Creek watershed.

Practically all recharge to the lowland aquifers is by infiltration of precipitation. These aquifers are estimated conservatively to receive about an average annual recharge of 40,000 acre-feet–but not all of the recharge can be captured by wells. Opportunities for induced artificial recharge may be favorable along the Stillaguamish flood plain upstream from Silvana. Artificial recharge may be feasible in the relict flood plain southwest of Arlington, although further investigations may show that the surficial materials are too fine.

The natural discharge of ground water is mostly into the Stillaguamish River and its tributaries, and into Puget Sound through submarine springs.

Quality of Ground Water

Water in most aquifers in the lowlands is generally low in dissolved solids and acceptable for practically all uses. Dissolved-solids concentration is usually less than 200 ppm and rarely exceeds 30 ppm. Hardness of water is generally in the 60-120 ppm range, and silica usually is between 20 and 40 ppm. Objectionable amounts of iron occur locally in the shallow aquifers, particularly beneath poorly drained areas where peaty or boggy soils are present. Brackish ground water has been reported in some wells in flood-plain and delta areas downstream from Silvana. However, significant salt-water encroachment has not been observed.

Utilization and Development

Ground water pumped in the lowlands is used mostly for municipal and industrial supply. Irrigation use of ground water is relatively small. In the Arlington area, water is produced from outwash and alluvium. Aquifers older than till supply water to municipal and industrial wells in the Stanwood area, and to wells owned by Marysville (though the town itself is in the adjacent Snohomish Basin). Water used for irrigation is produced mostly from shallow aquifers in alluvium or recessional outwash.

Pumping capacities of most municipal and industrial wells are less than 500 gpm. Figure 23 shows order-of-magnitude estimates of expected well yields in the study area. Owing to the complexity of subsurface deposits, however, yields might be obtained locally that are either much greater or much less than the quantity indicated on the map. The largest yields are from wells completed in alluvium along the Stillaguamish River and in recessional outwash on the relict flood plain southwest of Arlington. Only small yields are obtainable in the upland area west of Pilchuck Creek, on the uplands southeast of Arlington, and in areas where older consolidated rocks are exposed at land surface. Wells that tap deeper aquifers beneath valleys and low-lying areas near Puget Sound may flow.

MOUNTAINS

In the mountains, gravel and sand aquifers occur in Quaternary outwash and alluvial sediments that occupy about 150 square miles, principally in the valleys of the North and South Forks of the Stillaguamish River. Locally, the Quaternary deposits are 250 feet thick or more. Abundance of precipitation in the mountains suggests that the aquifers receive large quantities of recharge. In flood-plain areas, confined aquifers occur below clay lenses or till and wells drilled into these aquifers may flow.

Chemical quality of ground water is excellent except for locally undesirable iron content. The few wells in the mountains are generally less than 30 feet deep and are used mostly for domestic purposes. Yields as high as 250 gpm have been obtained from

wells penetrating water-bearing intervals of about 10 feet.

In areas where Quaternary sediments are absent, ground water is available only from consolidated rocks, in which well yields of only 10 gpm or less can be expected.

SNOHOMISH BASIN

SURFACE WATER

The Snohomish Basin comprises an area of 1,978 square miles, including 1,903 square miles of land and inland water. A map of the basin is shown on Figure 72. The Snohomish River, the largest stream in the basin, drains 1,780 square miles and flows into Possession Sound, an arm of Puget Sound, at the city of Everett. The Snohomish River is 22 miles long and extends upstream to the confluence of the Skykomish River which drains 844 square miles and the Snoqualmie River which drains 693 square miles. The upper half of the Snohomish drainage is a mountainous area that is part of the Cascade Range. Mountain valleys are narrow, and contain swift flowing streams maintained by generous rainfall and heavy snowpacks. Downstream, the valleys of the Skykomish and Snoqualmie Rivers widen, and the surrounding hills decrease in altitude. Below the junction of these two streams, the Snohomish Valley is 1 to 3 miles wide and the river has an average fall of 1.68 feet per mile. Marshes and tidal lowlands characterize the lower reaches of the river, and the stream is tidal for about its last 18 miles.

The Skykomish River begins at the junction of its North and South Forks near the town of Index, and flows westerly about 28 miles to its confluence with the Snoqualmie River. The river has an average fall of 8 feet per mile from Gold Bar to its mouth, a distance of 18 miles. Slopes in this reach range from 5 to 30 feet per mile.

The Snoqualmie River is formed by the junction of its North, Middle and South Forks near the town of North Bend, about 4 miles upstream from Snoqualmie Falls. Below the falls, the river flows northwesterly about 36 miles to its confluence with the Skykomish. The Snoqualmie River has a gradient of about 2 feet per mile from North Bend to Snoqualmie Falls at which point it drops 268 feet. From the base of the falls to Fall City the Snoqualmie drops about 10 feet per mile; from Fall City to its junction with the Skykomish, a distance of about 35 miles, it meanders through a broad valley where the average gradient is less than 2 feet per mile.

STREAMFLOW

Runoff Characteristics

Of the eleven basins in the Puget Sound area, the Snohomish ranks second in average annual runoff, with 7,100,000 acre-feet. Runoff from the higher altitudes between the Snoqualmie and Skykomish Rivers probably exceeds an average of 120 inches annually, and in the headwater areas of the Sultan River and the North Fork of the Skykomish, the runoff exceeds 140 inches annually. The lowest runoff-producing areas of this basin are in the vicinity of Everett. These lowland areas are influenced to some degree by the Olympic Mountains rain shadow, with the result that runoff averages less than 15 inches annually. For the entire basin runoff averages about 70 inches annually.

Tributary contributions from the high mountainous parts of the Skykomish River basin are represented by records obtained at gaging stations on the Beckler River, and the South and North Forks Skykomish River.

The highest unit runoff is produced in the North Fork basin, while the Beckler River drainage in the South Fork basin, is the lowest producer. Adjusted to the standard 30 year period, 1931-60, the record for the North Fork indicates a mean annual contribution of 1,230 cfs or 891,000 acre-feet. For this 146 square mile drainage area, these quantities are equivalent to 8.4 cfs per square mile. Judging by the adjusted record for its gage, the Beckler River produced a mean annual runoff of 608 cfs or 440,000 acre-feet per year. Unit runoff production in this basin averages about 2 cfs per square mile less than that of the North Fork area. Excluding the Beckler River contribution, runoff in the South Fork drainage averaged 1,870 cfs or 1,360,000 acre-feet per year. The unit runoff for this area is intermediate between that of the other two tributaries, amounting to 7.2 cfs per square mile.

The higher production of the North Fork drainage is the result of a more favorable orientation

of its catchment area with the direction of prevailing air-mass movements. Although the Beckler River system has a similar orientation, its mean basin altitude is slightly lower and the watershed is somewhat shielded from prevailing southwesterly storms by a major segment of the Cascade Range.

Runoff from the entire high-mountain part of the Skykomish River basin has been recorded at the gaging station near Gold Bar. Data collected at this site throughout 1931-60 show a mean annual discharge of 3,980 cfs (2,880,000 acre-feet per year). The mean unit runoff, 7.4 cfs per square mile, represents a composite for the two major upstream forks.

Although the drainage area of the Sultan River basin is relatively small (74 square miles) the production per unit area is higher than that recorded at any other major gaging site in the Puget Sound area. The adjusted 30-year mean, 589,000 acre-feet (813 cfs), is relatively small compared to that of large streams in the region, but the unit production is 11.0 cfs per square mile. Based on major gaging-station records, the nearest rivals to this watershed are the South Fork of the Skokomish River on the Olympic Peninsula, and the adjacent drainage of the South Fork of the Stillaguamish. Production from both of these watersheds, however, averages nearly 2 cfs per square mile less than the runoff generated in the Sultan basin.

A comparison of contributions from the three major forks of the Snoqualmie River shows the annual runoff of the Middle Fork (928,000 acre-feet, 1,280 cfs) to be about equal to the combined output of the other two. The average annual yield of the North Fork (538,000 acre-feet, 743 cfs) is about 20% more than that of the South Fork (443,000 acre-feet, 612 cfs). On a unit runoff basis, the production of the Middle and North Forks are comparable; 7.6 and 7.8 cfs per square mile, respectively. In contrast, the unit runoff of the South Fork is considerably lower–about 5.4 cfs per square mile–and is more comparable to the output of the adjacent and similarly oriented Cedar River basin. The higher values for the North and Middle Forks are the result of generally higher elevations and better exposure and catchment orientation to prevailing storms. The total average annual contribution of these three tributaries, as measured on the main stem near Snoqualmie, is about 2,640 cfs or 1,910,000 acre-feet per year. In terms of unit runoff, it is 7.0 cfs per square mile. This unit runoff is slightly less than that of the similarly mountainous part of the Skykomish River basin above the confluence of the main forks.

Runoff along the western face of the Cascade Mountains, between the major Skykomish River and Snoqualmie River drainages, has been measured on the Tolt River, a tributary to the Snoqualmie, at a gaging station near Carnation. Above this site, the Tolt drains about 81 square miles of foothills and mountain. The topography of the drainage area is ideal for the generation of copious amounts of precipitation. As a result, the drainage ranks third in unit runoff among the major tributary basins in this study area, being exceeded only by the Sultan River and North Fork Skykomish. Adjusted to the period 1931-60, the Tolt River yielded 636 cfs (461,000 acre-feet per year), which amounts to 7.8 cfs per square mile.

Contributions from the major upstream tributaries of the Snoqualmie River have been measured at a gaging station near Carnation. The excellent record at this site indicates an average annual runoff of 3,850 cfs (2,790,000 acre-feet per year) for the 30-year base period. The Puget Sound lowlands occupy a sizable portion of the drainage area above this gage, resulting in a reduction in the average unit discharge to 6.4 cfs per square mile.

Accurate continuous records of streamflow have not been possible in the Snohomish River proper because river stages are affected by tidal fluctuation. Projection of upstream records, however, suggests that the mean annual discharge of the entire Snohomish River system is probably about 9,500 cfs.

Long-term runoff trends for the Skykomish River near Gold Bar and Snoqualmie Rivet near Carnation are displayed in Figures 56 and 57. With only an occasional exception, the runoff patterns are similar, implying a high degree of uniformity in storm coverage over the entire basin. During water year 1959 the discharge of both streams was 140% of average for the 30-year base period. During water year 1941 the discharge of the Skykomish River was only 56% of the mean for 1931-60.

Mean monthly flows at five selected gaging sites in the Snohomish Basin are shown in Figures 58-62. Much of the runoff recorded at these stations is high-mountain snowmelt. Consequently, the normal high-flow period due to winter rains is followed by snowmelt peak flow in the spring. In general, the spring peak is more pronounced at the higher altitudes whereas the winter peaks becomes more dominant at lowland stations.

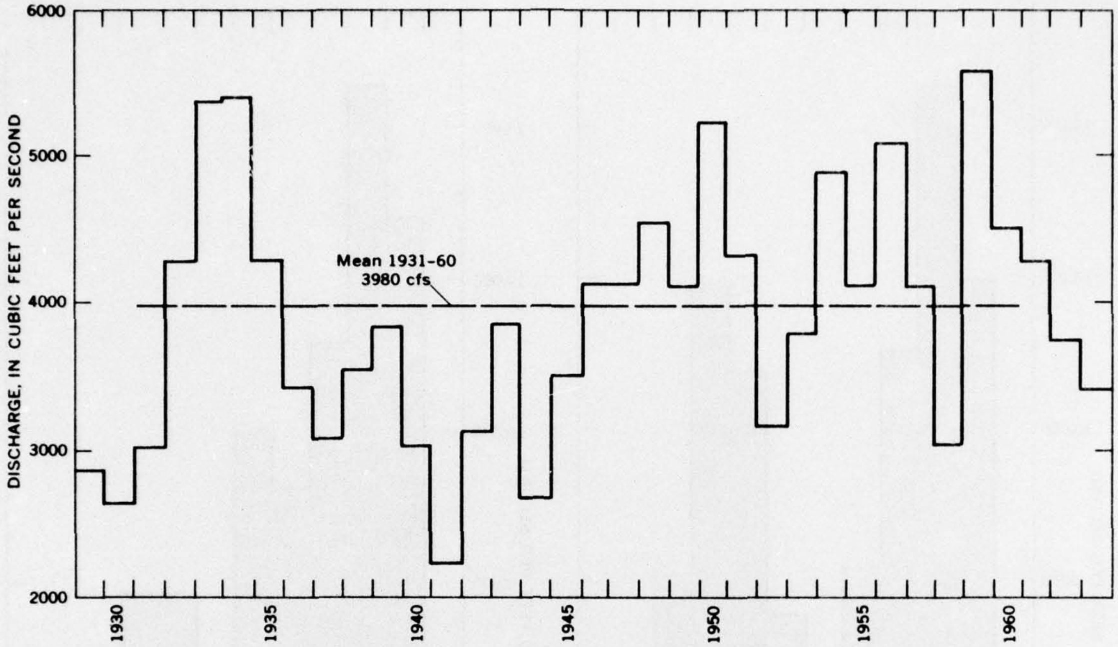


FIGURE 56.—Annual discharges, Skykomish River near Gold Bar.

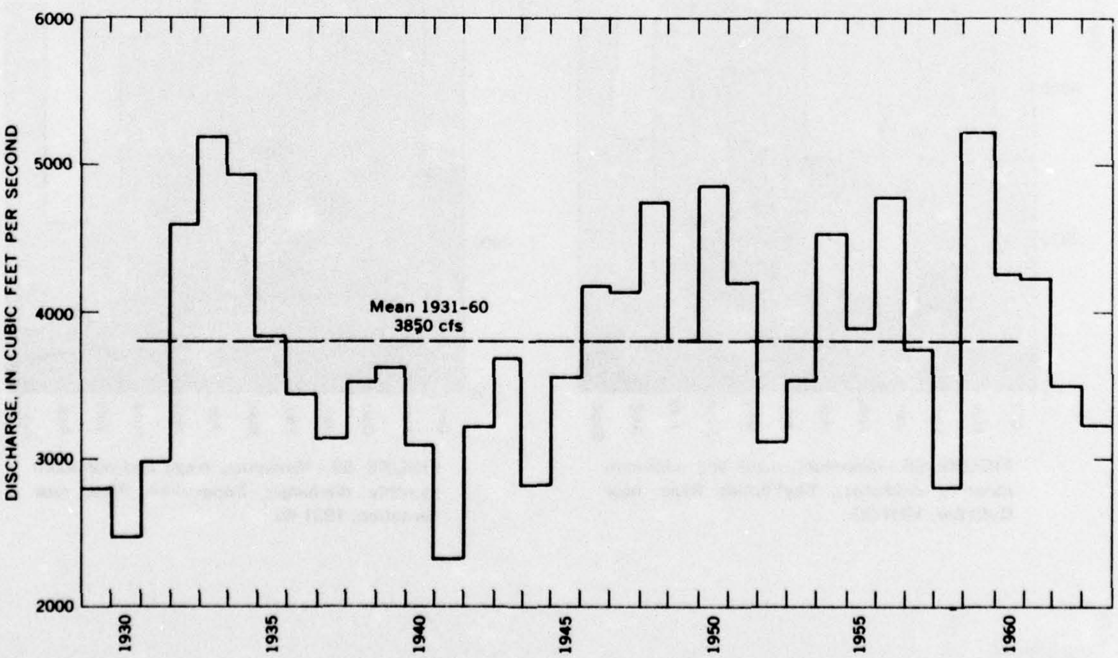


FIGURE 57.—Annual discharges, Snoqualmie River near Carnation.

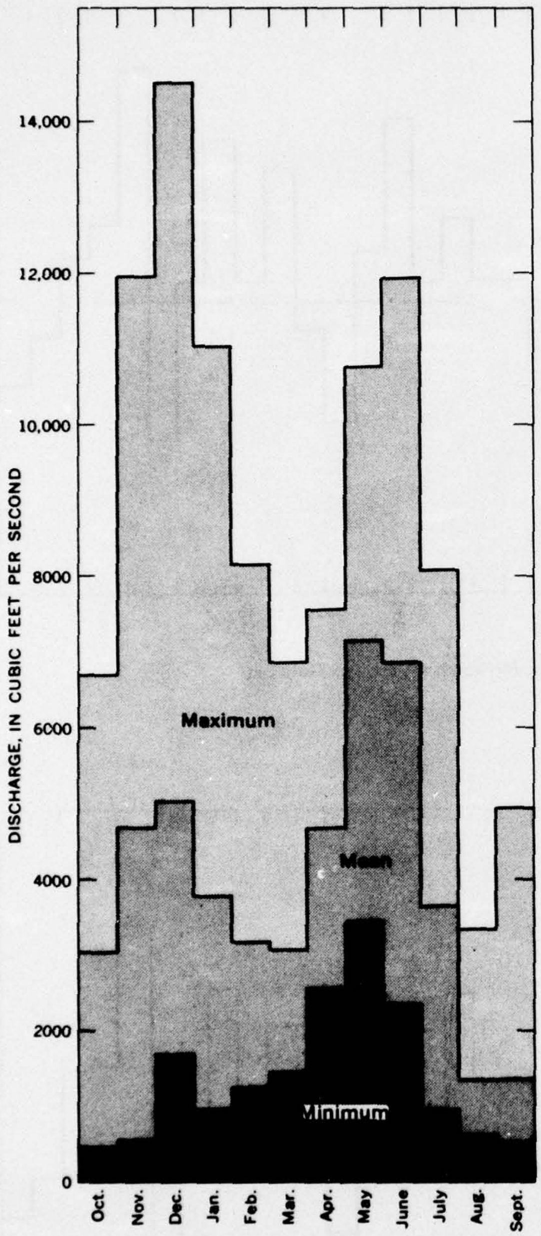


FIGURE 58.—Maximum, mean and minimum monthly discharges, Skykomish River near Gold Bar, 1931-60.

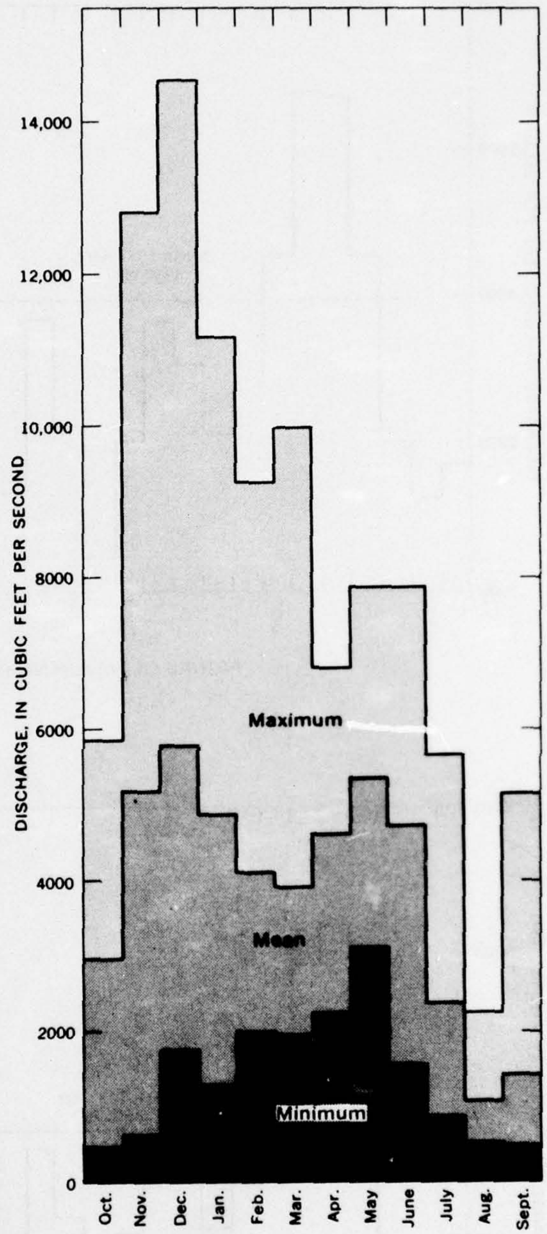


FIGURE 59.—Maximum, mean and minimum monthly discharges, Snoqualmie River near Carnation, 1931-60.

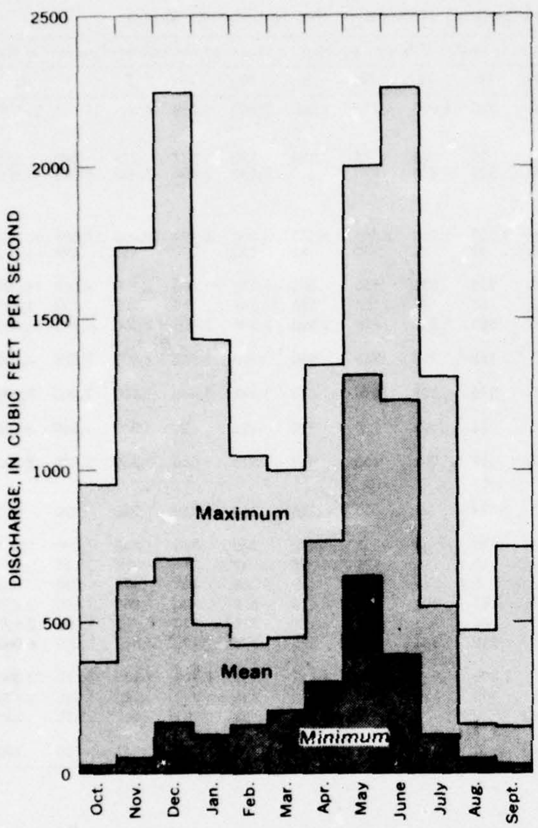


FIGURE 60.—Maximum, mean and minimum monthly discharges, Beckler River near Skykomish, 1931-60.

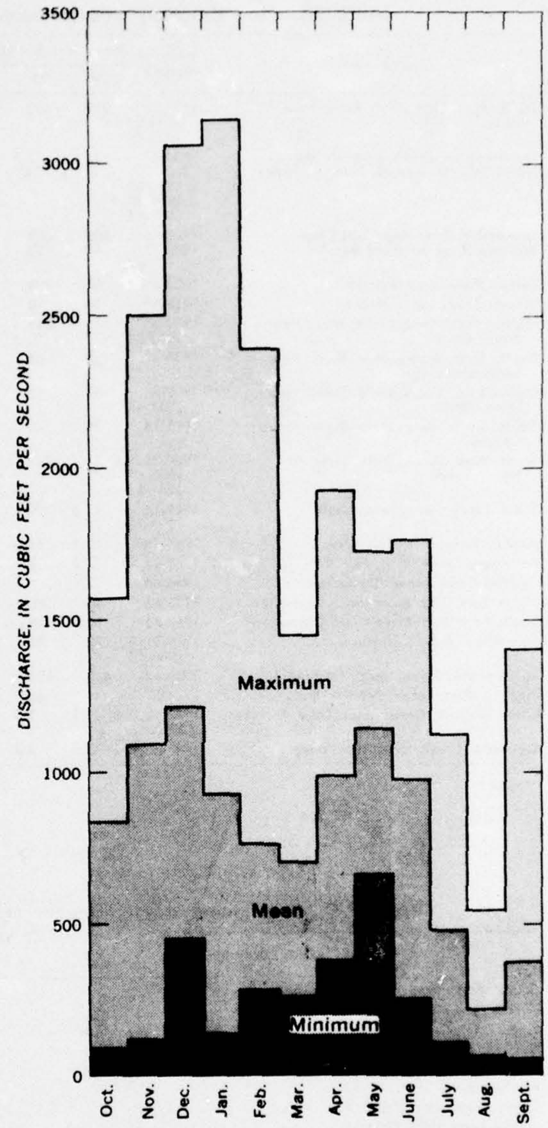


FIGURE 61.—Maximum, mean and minimum monthly discharges, Sultan River near Startup, 1931-60.

On the average, minimum monthly flows are recorded during August. In many years, however, summer recessions continue into the fall, causing the mean September flow to be about as low as that of August. Melt water from a few small permanent ice fields in this basin enhances the summer flows of several high-altitude tributaries; this source of supply is most evident in the drainages of the North and South Forks of the Skykomish River, Beckler River, and the Middle Fork Snoqualmie River. Ground-water contributions to summer flow are not appreciable along the upper reaches of streams in this basin, but this type of contribution does become increasingly significant in the broad valleys of the Puget Sound lowland.

Without exception, the greatest year-to-year variability in monthly flows is displayed during December, and the least variation occurs in August.

The variability of the daily flow of streams in the Snohomish Basin is presented as flow-duration data for selected gaging stations in Table 28.

TABLE 28.—Flow duration data for selected gaging stations in the Snohomish Basin

Gaging station	Period of analysis	Flow, in cubic feet per second, which was equaled or exceeded for indicated percent of time											
		99	95	90	80	70	50	30	20	10	5	1	0.1
South Fork Skykomish River near Index	1912, 1914-21 1923-64	320	405	500	740	1,020	1,710	2,800	3,600	5,050	6,600	11,700	25,000
Troublesome Creek near Index	1930-41	13	18.5	25	35	46	75	130	170	247	337	580	1,080
North Fork Skykomish River at Index	1911-12, 1914-22, 1930-38, 1947-48	123	174	220	330	455	810	1,400	1,880	2,600	3,400	6,200	14,000
Skykomish River near Gold Bar	1929-65	500	660	830	1,260	1,720	2,850	4,550	5,900	8,100	10,400	17,800	40,000
Wallace River at Gold Bar	1930-33, 1947-64	12	20	30	51	72	120	185	235	330	450	890	1,900
Sultan River near Startup	1935-65	62	100	140	225	320	550	870	1,120	1,600	2,200	4,600	11,000
Woods Creek near Monroe	1947-65	14	18	22	30	44	103	185	248	360	490	830	1,400
Middle Fork Snoqualmie River near North Bend	1909-26 1930-32	155	215	270	380	505	820	1,300	1,700	2,400	3,200	6,000	13,000
North Fork Snoqualmie River near Snoqualmie Falls	1930-49, 1962-65	43	66	91	145	205	348	560	720	1,040	1,400	2,550	4,900
North Fork Snoqualmie River near North Bend	1909-38(F) 1961-65	67	96	130	215	305	510	800	1,040	1,440	1,900	3,400	7,400
South Fork Snoqualmie River near Garcia	1911-15	30	40	48	64	84	160	290	405	620	860	1,660	5,200
South Fork Snoqualmie River at North Bend	1909-38(F) 1946-49, 1961-65	84	104	127	187	262	450	660	810	1,050	1,350	2,370	5,000
Tokul Creek near Snoqualmie	1909-14, 1930-31	15.5	20	25	34	47	80	125	160	210	260	420	810
Raging River near Fall City	1946-50	10.5	14	17	26	44	102	175	240	380	550	1,000	1,400
Patterson Creek near Fall City	1948-64	7.2	8.2	9.0	10.5	13	22	37	49	71	95	155	260
Griffin Creek near Carnation	1946-65	2.1	3.2	4.0	6.2	10.5	27	49	68	101	138	230	450
North Fork Tolt River near Carnation	1953-63	46	68	91	145	200	300	430	530	720	980	1,800	3,400
South Fork Tolt River near Carnation	1953-61	16.5	26	36	60	85	142	222	288	410	570	1,200	2,600
Tolt River near Carnation	1929-31, 1938-65	72	98	125	210	304	480	695	870	1,190	1,550	3,000	6,000
Snoqualmie River near Carnation	1930-64	475	620	780	1,300	1,920	3,080	4,450	5,450	7,300	9,400	18,000	33,000
Pilchuck River near Granite Falls	1944-57	34	45	58	100	150	250	375	480	710	990	1,820	3,650
Little Pilchuck Creek near Lake Stevens	1947-51, 1953-65	1.2	1.5	1.8	2.7	4.4	17	38	54	81	112	198	325
Quilceda Creek near Marysville	1947-65	3.5	4.3	4.9	6.1	7.9	16	30	41	59	77	125	190

TABLE 29.—Low-flow characteristics for selected gaging stations in the Snohomish Basin

Gaging station	Drainage area	Low-flow index	Slope index	Spacing index
South Fork Skykomish River near Skykomish	135	1.63	1.47	2.86
Beckler River near Skykomish	96.5	.89	1.47	4.42
S. Fork Skykomish River near Index	355	1.24	1.37	4.09
N. Fork Skykomish River at Index	146	1.30	1.59	4.90
Skykomish River near Gold Bar	535	1.38	1.72	4.19
Wallace River at Gold Bar	19.0	.84	1.92	7.25
Olney Creek near Gold Bar	8.31	.84	2.00	7.71
Sultan River near Startup	74.5	1.45	1.96	5.55
McCoy Creek near Sultan	5.87	.41	2.38	4.17
Woods Creek near Monroe	56.4	.32	1.56	2.78
Middle Fork Snoqualmie River near North Bend	169	1.43	1.89	4.17
N. Fork Snoqualmie River near Snoqualmie Falls	64.0	1.00	2.44	5.78
N. Fork Snoqualmie River near North Bend	95.7	1.01	2.22	5.11
S. Fork Snoqualmie River at North Bend	81.7	1.46	1.56	3.36
Raging River near Fall City	30.6	.33	1.59	4.80
Patterson Creek near Fall City	15.5	.54	1.30	1.68
Griffin Creek near Carnation	17.1	.19	1.78	3.75
N. Fork Tolt River near Carnation	39.2	1.69	1.89	3.94
S. Fork Tolt River near Carnation	19.7	1.22	2.18	5.42
Tolt River near Carnation	81.4	1.27	1.85	4.17
Stossel Creek near Carnation	5.58	.25	1.85	3.93
Snoqualmie River near Carnation	603	1.06	1.52	4.30
Pilchuck River near Granite Falls	54.5	.84	1.75	3.85
Little Pilchuck Creek near Lake Stevens	17.0	.08	2.86	4.50
Dubuque Creek near Lake Stevens	7.19	.03	8.33	14.5
Quilceda Creek near Marysville	15.4	.27	1.47	2.15

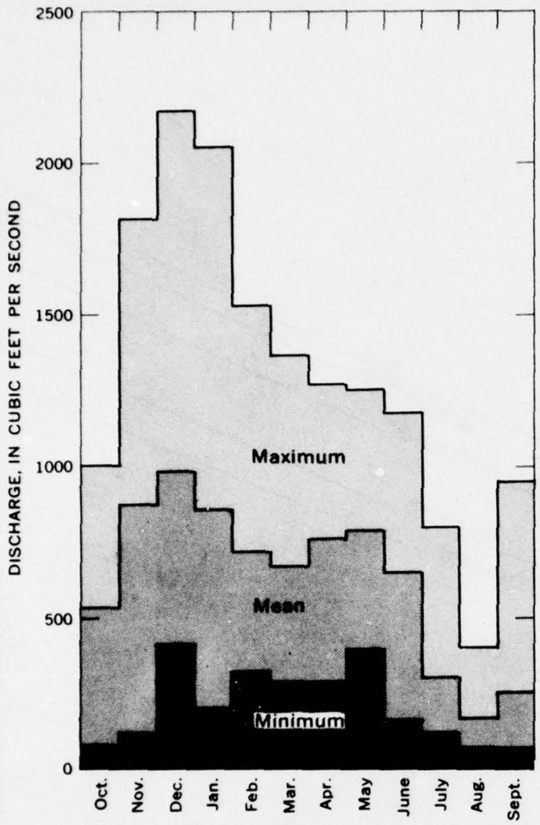


FIGURE 62.–Maximum, mean and minimum monthly discharges, Tolt River near Carnation, 1931-60.

Flood Characteristics

Floods caused by high rainfall with accompanying snowmelt are shown by characteristic sharp rises followed by recessions almost as rapid. Two or more peaks often occur within a period of two weeks. In general, the flow at the Skykomish gage peaks a few hours earlier than at the Snoqualmie gage, resulting in a broader flood peak for the Snohomish River. The maximum discharge of record on the Snohomish was 136,000 cfs, on February 10, 1951.

Flood-frequency curves for the Snohomish River at Snohomish, Skykomish River near Gold Bar, and Snoqualmie River near Carnation are presented in Figures 63-65. Frequency statistics were extended for these stations to longer periods by correlation with records for the station on the South Fork Skykomish River near Index, which has a 54-year record. The period of record and extended period for each station is as follows:

Station	Period of Record	Equivalent Record
Snohomish River at Snohomish	1942-64, 23 years	40 years
Skykomish River near Gold Bar	1929-64, 36 years	62 years
Snoqualmie River near Carnation	1930-64, 35 years	47 years

The abilityof a stream to transport large quantities of water without causing damage depends on channel characteristics. An understanding of these features can be characterized in part by a graphical representation of the stream's water-surface profile for various rates of discharge.

Water-surface profiles for the Snohomish, Snoqualmie, and Skykomish Rivers, shown in Figures 66-68, were plotted from observed or computed data. The 64,000 cfs profile for the Snohomish River is for an intermediate discharge, and does not represent a bank-full condition. The Snohomish River is 23 miles long and has no abrupt changes in gradient. Velocities shown on the 177,000 cfs profile are derived from backwater computations.

The 24,800 and 20,000 cfs profile for the Snoqualmie River approximate the bank-full condition. The Snoqualmie River has rather abrupt changes in gradient near river mile 23 and river mile 25, and has a waterfall near river mile 40. There is also a sharp change in gradient at river mile 0.42 on the Middle Fork Snoqualmie River. The velocities shown for the Snoqualmie River were obtained from backwater computations.

The 45,300 cfs profile for the Skykomish River represents a condition higher than bank full. On the basis of current data the Skykomish River has no abrupt changes in gradient between the mouth and river mile 22 except in the reach between river miles 15 and 19. The velocities shown for the Skykomish River were obtained from backwater computations.

Low-Flow Characteristics

Low-flow characteristics of streams in the Snohomish Basin are compared using indexes from low-flow frequency curves at 27 gaging stations (Table 29). The low-flow indexes are excellent in the upper South Fork Skykomish River and North Fork Tolt River basins (Fig. 22). In the basin above the

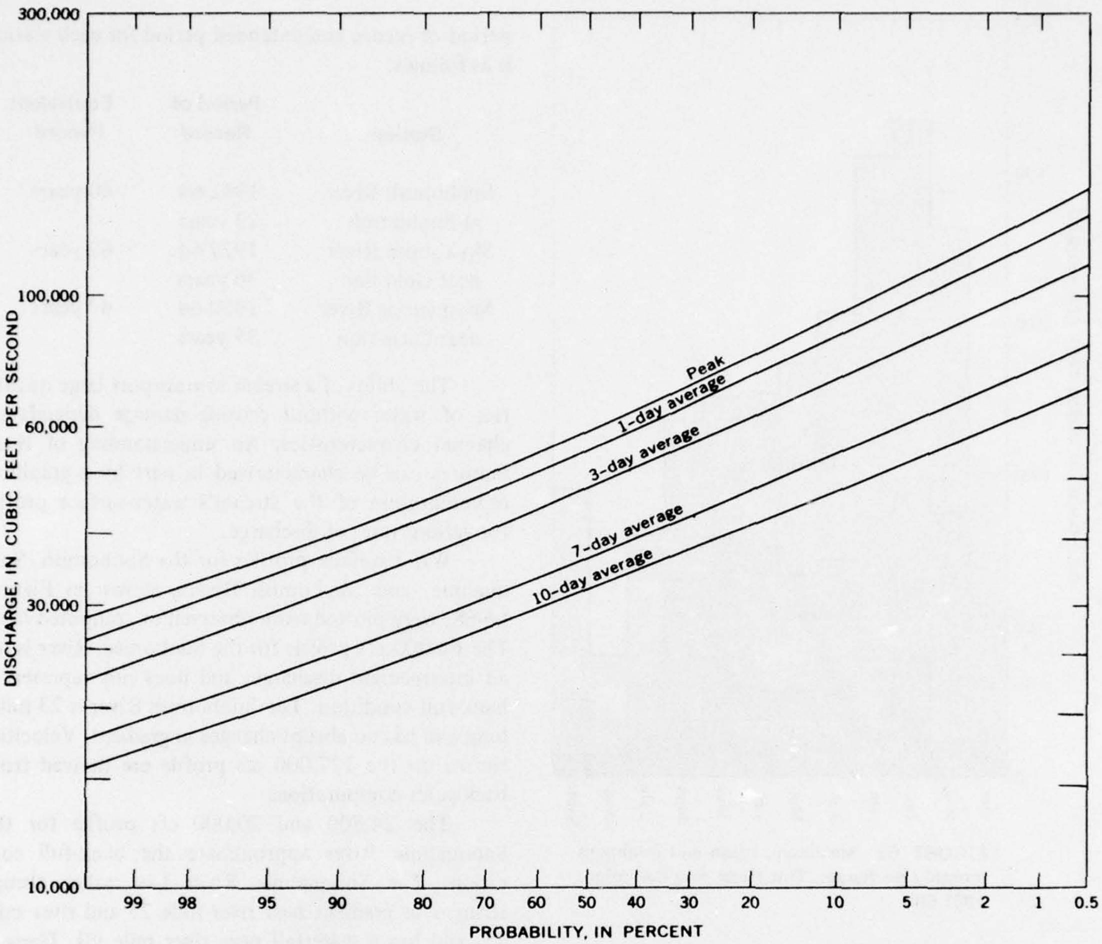


FIGURE 63.—Probability curves of annual maximum flows for specified time periods, Snohomish River at Snohomish.

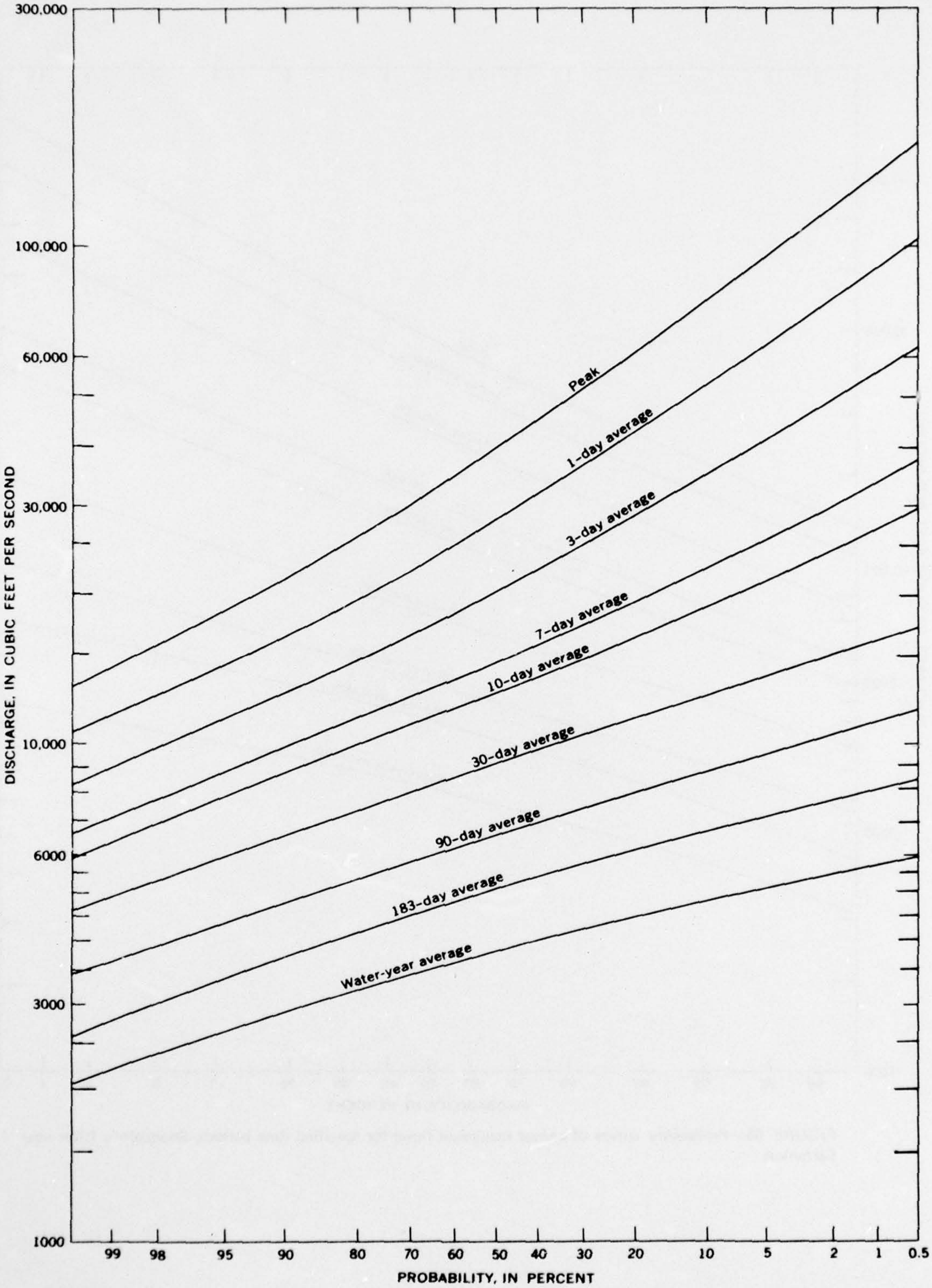


FIGURE 64.—*Probability curves of annual maximum flows for specified time periods, Skykomish River near Gold Bar.*

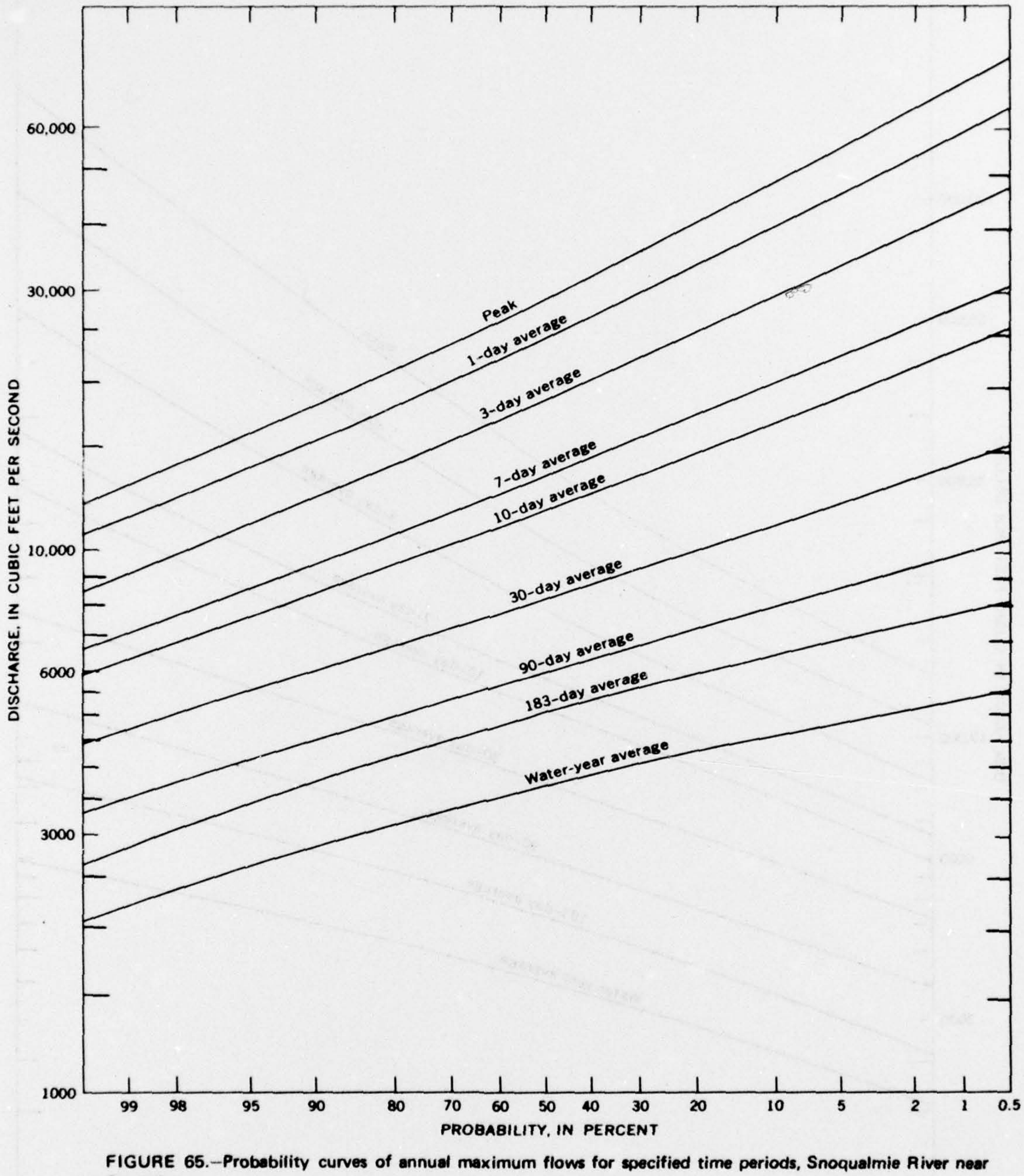


FIGURE 65.—Probability curves of annual maximum flows for specified time periods, Snoqualmie River near Carnation.

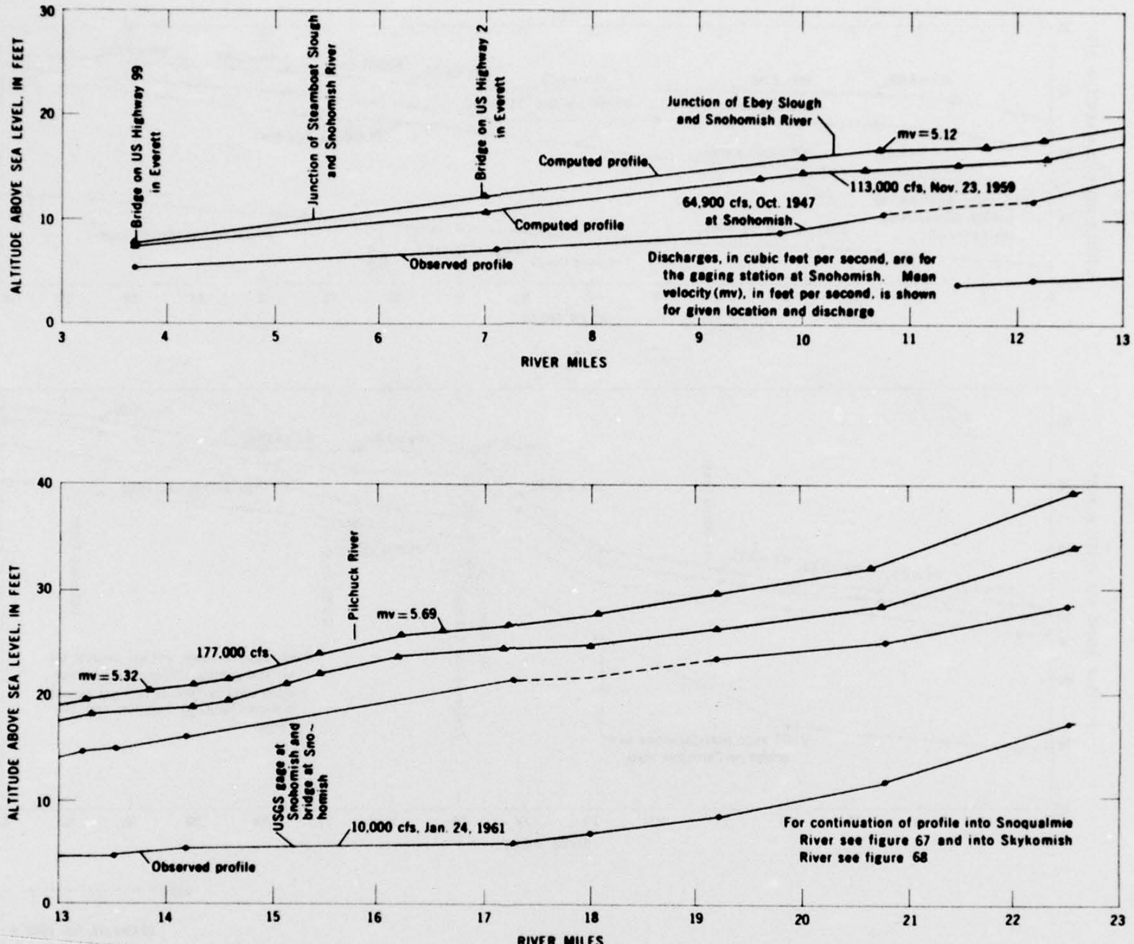


FIGURE 66.—Water-surface profile of Snohomish River, mile 3.5-23.

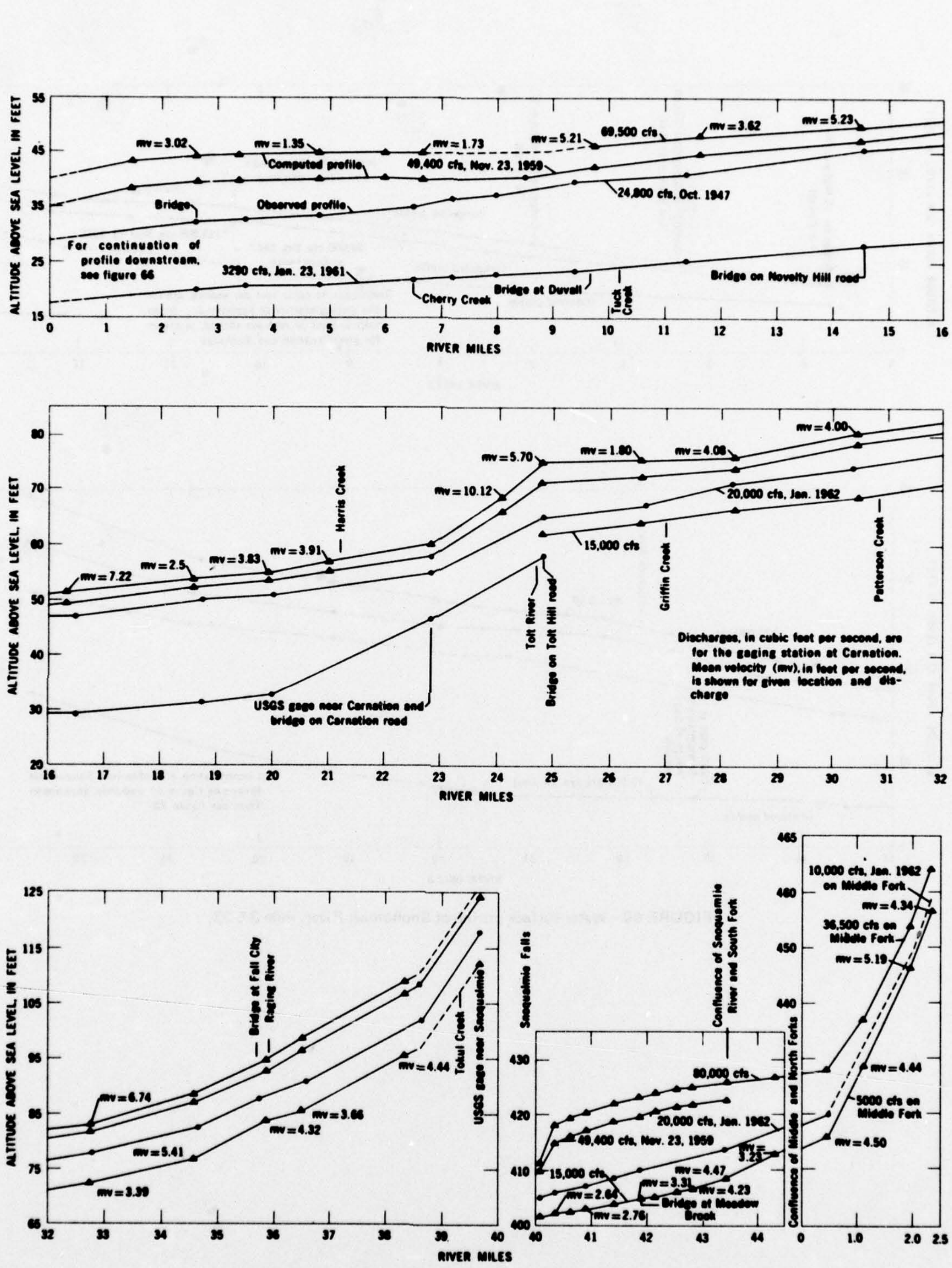
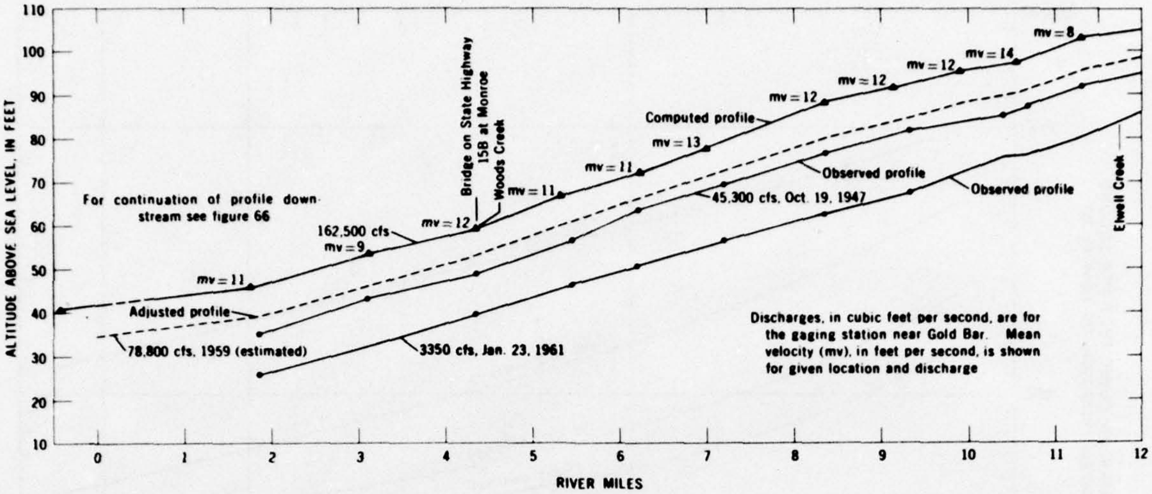


FIGURE 67.—Water-surface profiles of Snoqualmie River, mile 0-43.



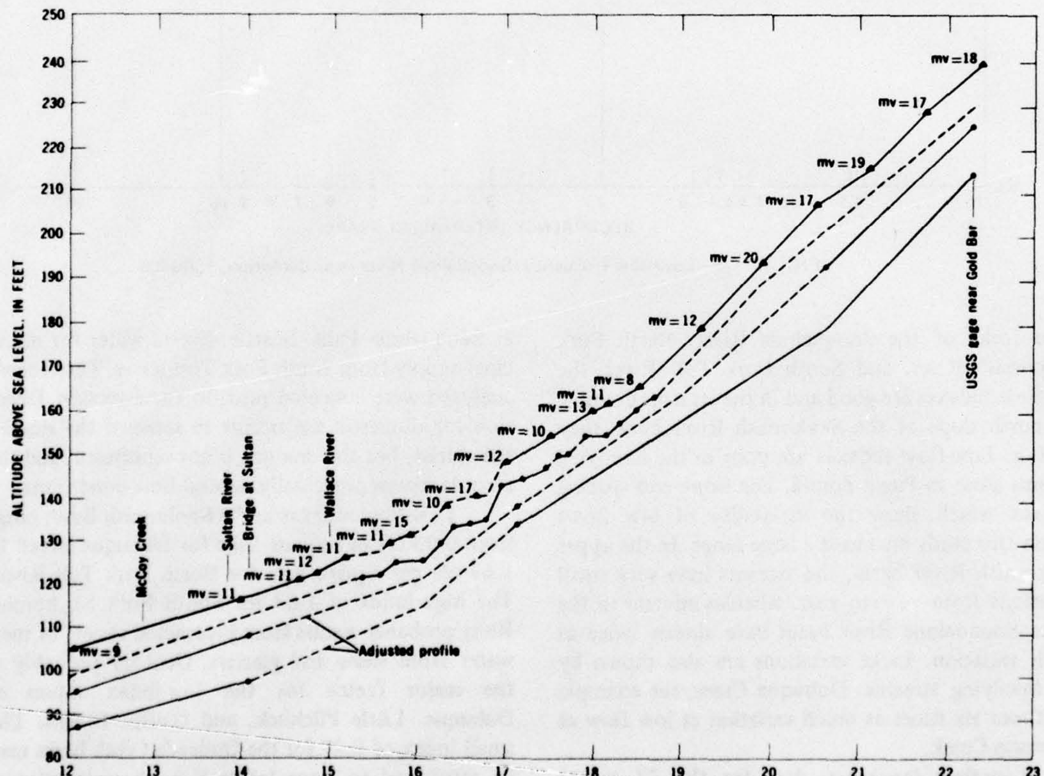


FIGURE 68.—Water-surface profile of Skykomish River, mile 0-22.

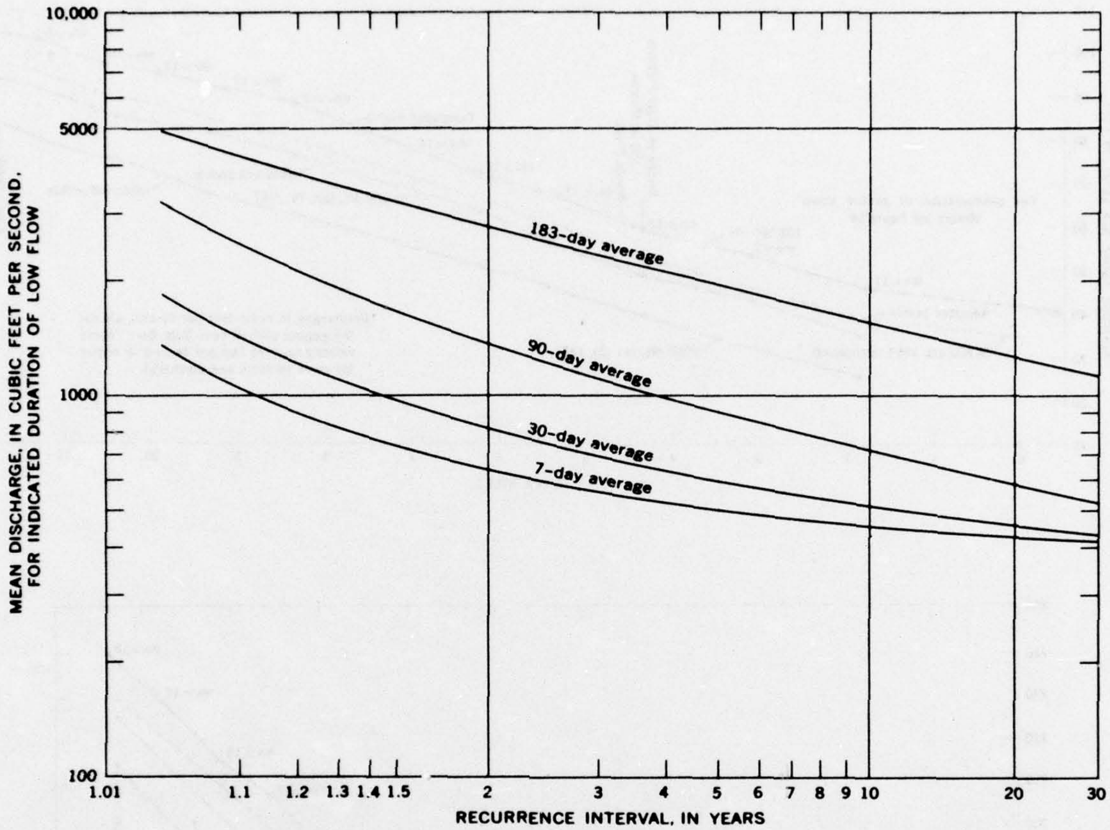


FIGURE 69.—*Low-flow frequency, Snoqualmie River near Carnation, 1946-63.*

three forks of the Snoqualmie River, North Fork Skykomish River, and South Fork Tolt River, the low-flow indexes are good and in the streams draining the north slope of the Skykomish River basin they are fair. Low-flow indexes are poor in the low-lying streams close to Puget Sound. The slope and spacing indexes which show the variability of low flows within this study area have a large range. In the upper Skykomish River basin, the streams have very small variations from year to year, whereas streams in the upper Snoqualmie River basin have almost twice as much variation. Large variations are also shown by the low-lying streams; Dubuque Creek for example has about six times as much variation at low flow as Patterson Creek.

Low-flow frequency data for the 27 gaging stations are listed in Table 30. Frequency curves for 2 of the 27 sites are shown in Figures 69 and 70.

The flow in the Snoqualmie River near Carnation is affected by regulation for power development at Snoqualmie Falls. Seattle diverts water for municipal supply from South Fork Tolt River. The records analyzed were collected prior to the diversion. Diversion for domestic use occurs in some of the smaller tributaries, but the amount is not significant, and the records represent virtually natural flow conditions.

Low-flow indexes in the Snohomish Basin range from 0.03 cfs per square mile for Dubuque Creek to 1.69 cfs per square mile for North Fork Tolt River. The high index of 1.63 for South Fork Skykomish River probably results from protracted runoff of melt water from snow and glaciers. Geology probably is the major factor for the low-index values of Dubuque. Little Pilchuck, and Griffin Creeks. The small index of 0.27 for the Quilceda Creek basin may be attributed to poor infiltration characteristics of soils and underlying sedimentary deposits.

The year-to-year variability of the low flows is indicated by the slope index. The indexes range from 1.30 for Patterson Creek to 8.33 for Dubuque

TABLE 30.—Low-flow frequency data for selected gaging stations in the Snohomish Basin
[Discharge, adjusted to base period April 1, 1946, to March 31, 1964]

Gaging station	Number of consecutive days	Streamflow in cfs, for indicated recurrence intervals, in years						
		1.05	1.30	2.0	5	10	20	30
South Fork Skykomish River near Skykomish	7	310	260	220	182	163	150	140
	30	390	320	260	210	182	165	155
	90	650	480	380	280	235	200	185
	183	980	770	630	480	420	360	330
Beckler River near Skykomish	7	140	105	86	70	64	59	57
	30	190	137	107	82	72	65	62
	90	400	250	178	120	100	85	78
	183	670	490	380	270	220	180	160
South Fork Skykomish River near Index	7	690	520	440	360	340	320	310
	30	900	670	540	430	390	360	340
	90	1,850	1,220	890	620	520	440	400
	183	3,150	2,300	1,800	1,300	1,100	940	860
North Fork Skykomish River at Index	7	310	240	190	150	132	119	112
	30	480	340	260	190	161	140	130
	90	900	590	430	290	235	200	180
	183	1,600	1,200	930	630	500	390	340
Skykomish River near Gold Bar	7	1,200	900	740	570	490	430	390
	30	1,580	1,200	950	700	580	500	450
	90	3,050	2,130	1,540	1,010	780	620	550
	183	5,000	3,900	3,100	2,150	1,700	1,380	1,220
Wallace River at Gold Bar	7	45	25	16	11	9.4	8.2	7.5
	30	71	37	23.5	15	12	10.4	9.6
	90	120	74	46	28	24	21.5	20.5
	183	177	142	116	86	70	59	53
Olney Creek near Gold Bar	7	18	10.3	7.0	4.8	4.1	3.5	3.2
	30	29.5	16.8	10.8	6.5	5.3	4.5	4.2
	90	69	38	24	13.8	10.3	8.3	7.5
	183	88	68	54	39	32	26.5	24
Sultan River near Startup	7	173	137	108	77	64	55	52
	30	265	190	143	100	80	66	60
	90	600	420	300	190	150	120	106
	183	1,010	770	600	420	340	280	250
McCoy Creek near Sultan	7	6.5	3.7	2.4	1.5	1.2	1.0	.9
	30	8.6	4.9	3.1	1.8	1.4	1.2	1.1
	90	12	6.7	4.2	2.6	2.0	1.7	1.5
	183	20	14	10	6.4	4.8	3.7	3.1
Woods Creek near Monroe	7	35	24	18	14	12.5	11.5	11
	30	43	27.5	20.5	15.4	13.7	12.6	12
	90	54	34	25	18	16	14.4	13.8
	183	100	68	50	34	27	27	19.5
Middle Fork Snoqualmie River near North Bend	7	490	335	240	163	140	128	120
	30	750	470	315	213	180	160	150
	90	1,200	730	480	320	270	240	225
	183	1,720	1,300	1,000	700	560	450	400
North Fork Snoqualmie River near Snoqualmie Falls	7	160	94	64	40	32	26	24
	30	200	125	86	54	42	33	29
	90	390	250	165	95	68	50	43
	183	620	470	370	270	225	190	170
North Fork Snoqualmie River near North Bend	7	230	144	96	61	50	43	39
	30	300	187	128	80	62	50	44
	90	520	350	235	138	102	81	74
	183	800	620	490	360	290	245	220
South Fork Snoqualmie River at North Bend	7	185	146	119	94	83	76	73
	30	235	170	132	103	92	84	81
	90	400	260	185	136	120	110	103
	183	640	500	400	285	230	185	165
Raging River near Fall City	7	20	13	10	7.7	6.9	6.3	6.0
	30	25	16	12	9.7	8.6	8.0	7.7
	90	45	25.5	18	13	11.3	10.2	9.7
	183	97	64	48	34	29	25	24
Stossel Creek near Carnation	7	3.5	2.1	1.4	1.0	0.9	0.8	0.7
	30	4.3	2.6	1.8	1.2	1.0	.9	.8
	90	7.4	3.5	2.3	1.6	1.3	1.2	1.1
	183	14	8.3	5.5	3.3	2.6	2.2	2.0
Snoqualmie River near Carnation	7	1,200	830	640	500	450	425	410
	30	1,650	1,100	820	600	510	450	430
	90	2,950	1,900	1,370	900	710	570	510
	183	4,600	3,500	2,750	1,900	1,530	1,250	1,100
Pilchuck River near Granite Falls	7	82	59	46	35	30	26	24
	30	110	74	54	39	33	29	27
	90	210	130	87	56	46	40	37
	183	300	225	177	126	104	87	79

TABLE 30.—Continued

Gaging station	Number of consecutive days	Streamflow in cfs, for indicated recurrence intervals, in years						
		1.05	1.30	2.0	5	10	20	30
Little Pilchuck Creek near Lake Stevens	7	2.5	1.8	1.4	.9	.7	.5	.4
	30	3.4	2.2	1.6	1.2	1.0	.9	.8
	90	4.8	2.9	2.2	1.6	1.4	1.3	1.2
	183	17.5	9.9	6.3	3.5	2.5	1.8	1.6
Dubuque Creek near Lake Stevens	7	.8	.4	.2	.1	0	0	0
	30	1.3	.6	.3	.2	.1	.04	0
	90	2.7	1.1	.5	.3	.2	.1	.1
	183	8.8	5.0	2.9	1.3	.8	.5	.4
Patterson Creek near Fall City	7	12	9.6	8.3	7.1	6.6	6.4	6.2
	30	13	10.5	9.0	7.6	7.0	6.7	6.4
	90	14	11.6	9.9	8.3	7.6	7.0	6.8
	183	19.8	16.5	13.9	10.7	9.0	7.8	7.2
Griffin Creek near Carnation	7	7.8	4.3	3.2	2.4	2.1	1.8	1.7
	30	9.1	5.1	3.6	2.7	2.3	2.0	1.9
	90	16.5	7.3	4.9	3.5	3.0	2.6	2.4
	183	31	17.8	12	7.6	6.0	5.0	4.5
North Fork Tolt River near Carnation	7	137	89	66	47	40	35	33
	30	164	115	86	60	49	40	37
	90	280	195	138	85	66	54	48
	183	430	330	260	190	155	128	115
South Fork Tolt River near Carnation	7	49	33	24	16	13	11	10
	30	63	44	33	22.5	18	14.8	13
	90	136	95	66	39	28.5	22	19
	183	245	170	130	94	78	68	62
Tolt River near Carnation	7	205	140	103	75	64	56	52
	30	250	175	130	91	75	63	57
	90	440	310	220	138	102	80	70
	183	740	560	430	305	245	200	180
Quilceda Creek near Marysville	7	5.6	4.7	4.1	3.4	3.1	2.8	2.7
	30	6.6	5.3	4.5	3.7	3.3	3.0	2.9
	90	8.6	6.4	5.3	4.5	4.1	3.8	3.6
	183	14.5	11	8.8	6.7	5.8	5.0	4.6

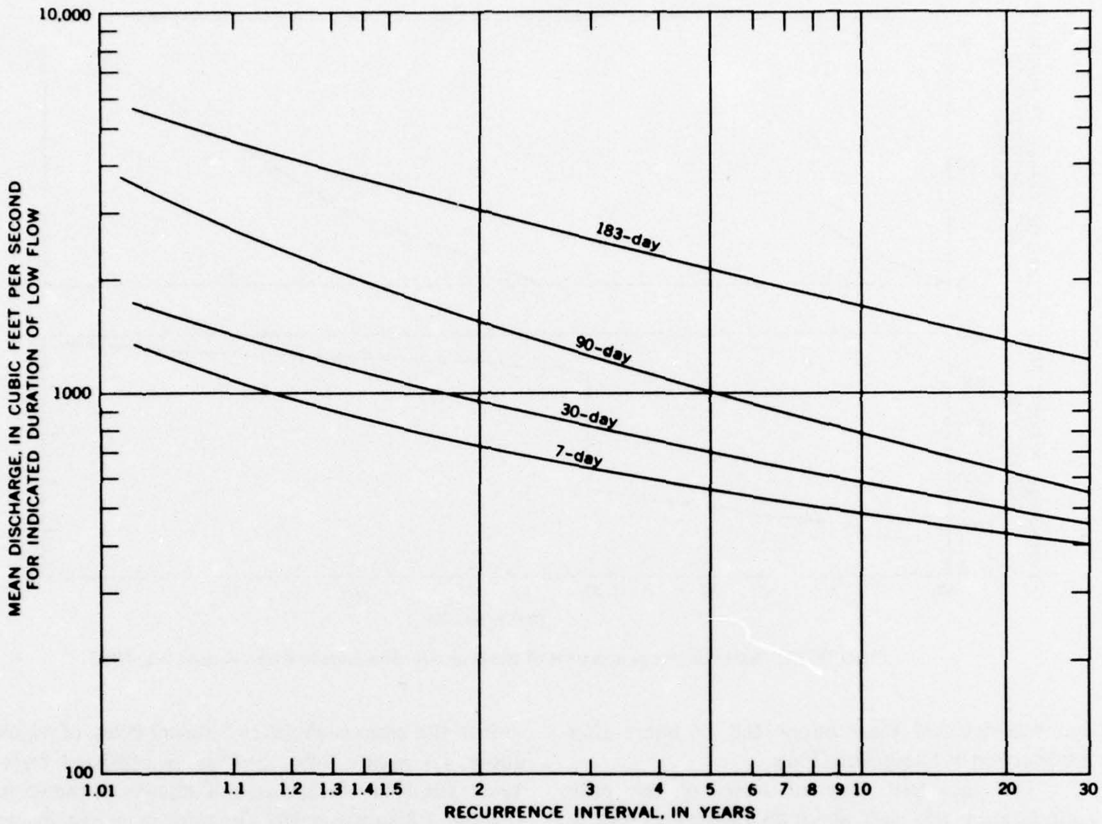


FIGURE 70.—Low-flow frequency, Skykomish River near Gold Bar, 1946-63.

Creek. Those for the upper Skykomish River stations and for a few of the streams in lower areas are fairly low. In the upper Skykomish, glacial melt water may account for the small variation. In the low-lying areas ground-water discharge from the extensive alluvial and outwash sediments may be the reason. Slope indexes for most of the remaining streams are greater than the regional average, possibly because flow-sustaining contributions from ground-water storage are small.

The spacing index of low-flow frequency curves in the basin range from 1.68 for Patterson Creek to 14.5 for Dubuque Creek. Much of the basin is underlain by rather impermeable rocks that favor immediate surface runoff, which may account for the large indexes computed for many of the streams. Olney Creek and Wallace River have spacing indexes of 7.71 and 7.25, which are among the highest in the Puget Sound Study Area.

Dispersion and Time of Travel

Dispersion and time-of-travel studies for the Snoqualmie River were made by the U.S. Geological Survey in the reach between the gaging station below Snoqualmie Falls and the community of High Rock on August 2-3, 1966 using fluorescent dye rhodomine B. Profiles of discharge and of travel time of maximum dye concentration are illustrated on Figure 71.

Discharge of the Snoqualmie River during this study ranged from 1,000 cfs at the Snoqualmie Falls gaging station to about 1,500 cfs at High Rock. The most significant gain in streamflow, about 250 cfs, occurred at the Tolt River confluence.

In the reach between Snoqualmie Falls and Carnation, dispersion and time-of-travel data were obtained only at Fall City, which is 4 miles downstream from the falls. Attempts to obtain data farther downstream at Carnation were abandoned because no

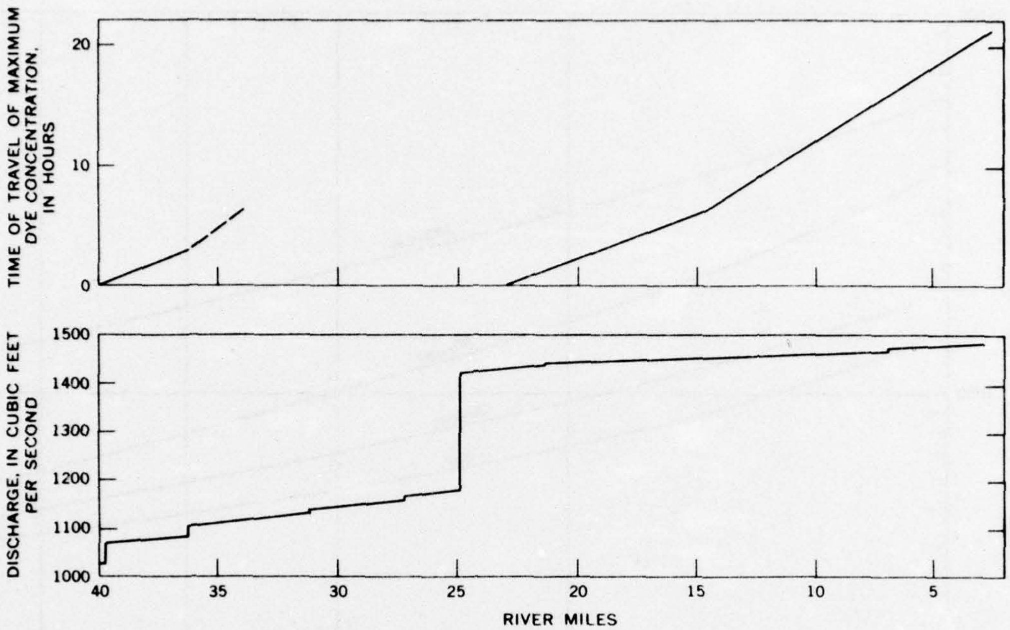


FIGURE 71.—Water discharge and time of travel of dye, Snoqualmie River, August 2-3, 1966.

dye was detected there during the 17 hours after introduction at Snoqualmie Falls.

The measured time of travel of the peak concentration was least, about 46 minutes per mile in the 8.3-mile reach between Carnation and Novelty Hill. It apparently was greatest—more than 76 minutes per mile—in the 11.1 mile reach below Fall City. The average time of travel of the peak concentration for the 20.2-mile reach between Carnation and High Rock was about 64 minutes per mile.

The dispersion coefficient computed from the data, about 300 square feet per second in the Carnation-High Rock reach, is typical of broad-channel meandering streams; it compares favorably with similar values computed in adjacent lowland rivers—the Green and the Stillaguamish. The dispersion coefficient for the Snoqualmie Falls-Carnation reach could not be determined.

STORAGE AND REGULATION

Natural Surface Storage

The total amount of storage in lakes and the glaciers in the Snohomish Basin is not known, but the surface area covered by these bodies can be used to provide at least a comparative indication of the amount of water that is stored. The total lake surface in the basin is about 21.5 square miles, of which about 4.4 square miles consists of regulated reservoirs. The total surface area of glaciers in the basin is about 1.8 square miles. The most extensive glacier system is in the upper watershed of the South Fork Skykomish River.

Reservoirs

The following discussions of existing and potential reservoirs in the Snohomish Basin is restricted mainly to those with capacities of more than 5,000 acre-feet. Two potential reservoirs of smaller size are included because of their importance to projects having larger storage. Existing reservoirs and potential storage sites in the basin are shown in Figure 72.

Existing Reservoirs—The Snohomish County Public Utility District and the city of Everett have jointly undertaken a dam and reservoir project on the Sultan River which presently provides 34,500 acre-feet of water-supply storage for Everett. Provisions have been made for an additional storage and hydroelectric facilities in the future. Chaplain Lake provides intermediate storage for 14,000 acre-feet of municipal water from the Sultan River. The construction of additional storage facilities may have an important effect on the flow regimen of the Sultan River. Flows presently drop to less than 100 cfs

during the summer, yet the diversion capability of the Everett system is already 180 cfs, and future diversion capability is planned to be approximately 490 cfs.

A run-of-river power plant is operated by the Puget Sound Power & Light Co. on the Snoqualmie River at Snoqualmie Falls. Low flows of the river are affected slightly. In 1963, the city of Seattle completed a dam on the South Fork Tolt River to store 60,000 acre-feet of water for municipal supply as a supplement to its Cedar River system. Detailed information on principal existing reservoirs in the basin is presented in Table 31.

Potential Storage Sites A comparatively large number of potential reservoir sites occur in the Snohomish River Basin. Twenty-eight of these sites are shown on Figure 72 and additional data are given in Table 32.

DIVERSIONS

Within the Snohomish Basin, a complex system of dams and diversions has evolved in the Sultan River watershed through the combined efforts of the city of Everett and the Snohomish County Public Utility District No. 1. This system supplies the Everett metropolitan area with water for municipal and industrial use and may provide storage for power development and flood control.

The city of Everett in collaboration with the Snohomish County Public Utility District No. 1 operates a dam on the upper Sultan River primarily for municipal supply. Water is released from this reservoir, and at a small diversion dam about two miles east of Chaplain Lake, the city diverts about 180 cfs from the river into its municipal supply system.

The city of Seattle diverts 140 cfs from its South Fork Tolt River Storage Reservoir for municipal supply. The ultimate plan for this development provides for diverting the North Fork Tolt River into the existing regulating reservoir with the combined rate of diversions to be limited to 280 cfs. An agreement with the city of Seattle establishes minimum release below the South Fork Dam for fisheries use.

The Puget Sound Power & Light Co. operates two hydroelectric generating plants on the Snoqualmie River at Snoqualmie Falls. About 620 cfs is diverted to Plant No. 1 which is about 260 feet directly below the intake structure and surface building. Discharge from the tailrace of Plant No. 1 is returned directly to the river at the base of the falls. The intake for Plant No. 2 is in the right bank immediately above the crest of Snoqualmie Falls. From this point as much as 1,900 cfs is diverted to Plant No. 2 about 1,400 feet downstream from the base of the falls and then returned to the stream.

The city of Snohomish diverts water from two places along the Pilchuck River. Though the city holds rights for 46 cfs, only 5 cfs is diverted, about 3 cfs is used for municipal supply and 2 cfs for power generation. Of the municipal diversion, a part is returned to the Snohomish River as sewage effluent.

The Weyerhaeuser Co. maintains two large diversions from the lower reaches of the Snohomish River. About a mile above the mouth, 47 cfs is pumped from the river for cooling and log-washing operations and is returned to the river within 300 feet of the point of diversion. The other diversion, 56 cfs, is made from Ebey Slough, a distributary of Snohomish River, for use at a kraft pulpmill in Everett near the mouth of the Snohomish River. The waste water is discharged to tidewater.

The Snoqualmie Falls Timber Co. diverts 15 cfs from Tokul Creek for boiler supply and other manufacturing operations and to provide the community of Snoqualmie Falls with domestic water. That part of the water used in the mill is discharged into the Snoqualmie River.

The Washington Department of Fisheries Skykomish River Salmon Hatchery on May Creek, tributary of the Wallace River, diverts 10 cfs from May Creek which is returned to the creek below the hatchery ponds. The Department of Fisheries fishway and trapping facilities at Sunset Falls diverts 180 cfs through the fishway that is returned at the base of the falls.

About 6,800 acre-feet of water was diverted for irrigation in the Snohomish Basin in 1965; most of the irrigation was in the lower parts of the Skykomish, Snoqualmie, and Snohomish River basins.

QUALITY OF SURFACE WATER

Chemical and Sanitary Quality

The surface waters of the Snohomish Basin are of excellent chemical quality. The flows of the Snohomish, Skykomish, and Snoqualmie Rivers are very soft, dilute water. Dissolved-solids and hardness values for these waters rarely exceed 40 ppm.

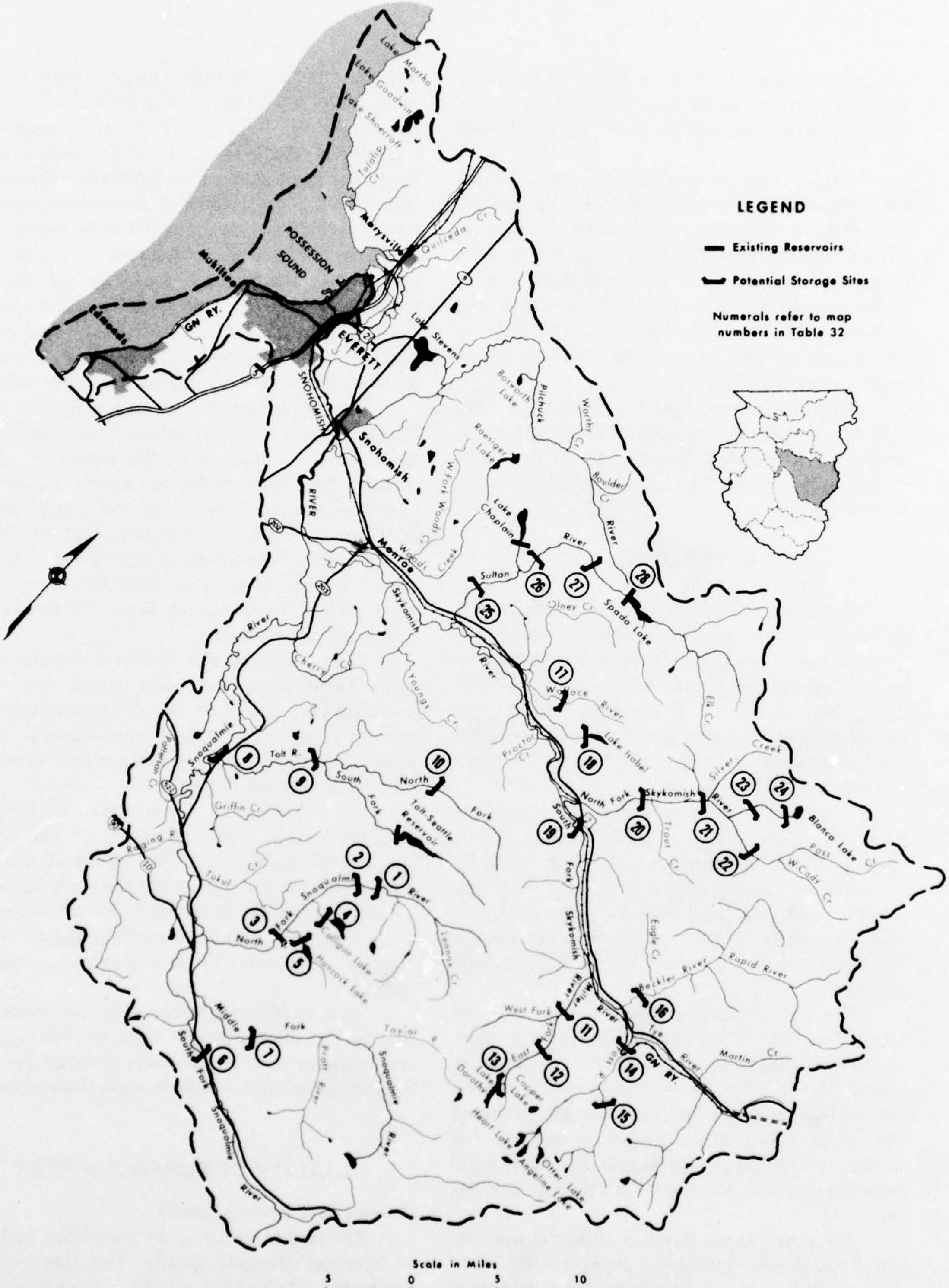


Figure 72. Existing Reservoirs and Potential Storage Sites in the Snohomish Basin

TABLE 31.—Existing reservoirs in the Snohomish Basin

P, Hydro-electric development; WS, Municipal and industrial water supply.

Name	Location Stream, T-R-S	Drainage area (sq mi)	Storage (Acre-ft) Active	Inactive and/or dead	Total	Dam dimensions Ht (ft)	Width (ft)	Reservoir area (acres)	Use	Applicant or owner	Remarks
Lake Spada (Sultan Res. #1 Culmback Dam)	Sultan R. 29-9-9				34,000 (phase 1 of construction)	310	320	1,527	P, WS	PUD #1 Snohomish Co. and City of Everett	Phase 2 would have 98,000 acre-ft active storage.
Chaplain Lake	Chaplain Cr. 28-8-6		13,400	600	14,000	22	600	444	WS	City of Everett	Stores water from Sultan River.
Tolt Res.	S.Fk. Tolt R. 26-9-32		53,000	7,000	60,000	170	1,000	850	WS	City of Seattle	

TABLE 32.—Potential storage sites in the Snohomish Basin

Map no.	Project name	T-R-S	River and mile	Total storage (1,000 acre-ft)	Drainage area (sq mi)	Remarks
1	Upper N.F.	25-9-16	N. F. Snoqualmie 12.7	100	52	
2	Lower N.F.	25-9-20	N. F. Snoqualmie 11.7	165	58	
3	Mile 5.9	24-8-13	N. F. Snoqualmie 5.9	--	85	Pondage regulating reservoir for Lower N. F.
4	Calligan Lake	25-9-32	Calligan Cr.	44	15	Water Dist. 97, King Co.
5	Hancock Lake	24-9-8	Black Cr.			
6	Twin Falls	23-9-29	S. F. Snoqualmie	--	56	
7	M. F. Snoqualmie (Mount Si)	23-9-10 23-9-15	M. F. Snoqualmie 10	129	160	U. S. Corps of Engineeres
8	Carnation	25-7-21	Tolt R. 2	--	--	Water Dist. 97, King Co.
9	Forks	26-8-31	Tolt R.	11	81	
10	Dry Cr.	26-9-8	N. F. Tolt R. 10	69	22	City of Seattle proposal
11	Miller Forks	25-11-8	Miller R. 4	--	40	
12	E. Fk. Miller	25-11-22	E. Fk. Miller	--	14	
13	Lake Dorothy	24-11-3	E. Fk. Miller	32	6	
14	Tonga	26-12-32	Foss R. 1.5	9	46	
15	Alturas Lake	25-12-21	E. Fk. Foss	9	21	
16	Beckler	26-11-24	Beckler R. 2	11	96	
17	Wallace Falls	28-9-27	E. F. Wallace R.	51	18	
18	Lake Isabel	28-9-36	May Cr. 5.2	8	3	
19	Sunset Falls	27-10-29	S. F. Skykomish	--	355	
20	Trout Cr.	28-10-35 27-10-2	N. F. Skykomish 6	250	145	
21	Silver Cr.	28-11-19 28-11-20	N. F. Skokomish 10	--	95	
22	Troublesome Cr.	28-11-26	N. F. Skokomish 14	--	--	
23	Troublesome #2	28-11-21	Troublesome Cr. 2.2	--	10	
24	Troublesome (Blanca Lk.)	28-11-14	Troublesome Cr. 4.2	15	3	
25	Winter Cr.	28-8-17	Sultan R. 5.3	--	95	Snohomish Co. PUD #1 (FPC Permit #2157)
26	Lower Sultan	29-8-32	Sultan R. 10.3	5	80	Snohomish Co. PUD #1 (FPC Permit #2157)
27	Middle Sultan	29-8-26	Sultan R. 13.4	4	72	Snohomish Co. PUD #1 (FPC Permit #2157)
28	Upper Sultan (Culmback)	29-9-29	Sultan R.	100 [1]212	69	Snohomish Co. PUD #1 (FPC Permit #2157) City of Everett (FPC Permit #2157) at existing Culmback Dam (Lake Spada)

Table 58 summarizes data for the Snohomish River at Snohomish. These data are typical to those for the Skykomish near Gold Bar, Sultan River at Sultan, Snoqualmie River at Snoqualmie, and Tolt River near Carnation.

The turbidity of the Snohomish is rather low compared to the other streams on the east side of the Puget Sound Area. The mean turbidity of the Snohomish River at Snohomish was 16 JTU for 7 years of daily and monthly sampling. The maximum turbidity at this point, occurring during storm runoff, was only 160 JTU (Table 58). The turbidity of the Skykomish River is appreciably less than that of the Snohomish and the Snoqualmie turbidity values are slightly greater than those of the Snohomish. Turbidity is low because the glaciers in this basin are small and contribute little to streamflow.

Sanitary quality deteriorates somewhat from the headwaters to the mouth in the Snohomish River drainage system. The Skykomish River is generally of very excellent sanitary quality with MPN values usually not more than 50. However, concentrations of coliform bacteria increase somewhat in the lower Skykomish before it joins the Snoqualmie to form the Snohomish River. MPN values of Snoqualmie River at Snoqualmie are highly variable. During the summer and fall coliform bacteria have reached 4,600 MPN or more. Sampling of the Snohomish River at Snohomish reveals the composite effect of the upper two rivers, together with some increase in sanitary wastes below their confluence. The data at the lower station indicated a mean MPN of slightly less than 2,000, with an observed maximum of 24,000.

Stream Temperatures

Temperature records are available for six streams in the Snohomish Basin (Table 59). A thermograph is in operation on only one, the Wallace River at Gold Bar. The January minimum temperature of all streams ranges from 32°F to 34°F. The period of near-freezing minimum temperature is shortest (January) for the Tolt River near Carnation and longest (November-March) for the Wallace River. Fluctuations in temperature shown by most streams seem small in comparison to those in the Wallace River, largely due to a more precise identification of temperature ranges based on continuous thermograph records on the Wallace. The maximum temperature of 74°F for the Snoqualmie River near Carnation in August is the highest in the basin. The high temperatures reflect the lengthy travel time through lowlands, providing opportunity for absorption of solar radiation even though the river's flow is comparatively large.

Sediment Transport

Sediment transport is discussed for two physiographically different parts of the basin—the upper and lower drainages. The upper consists of areas above the confluences of the North and South Forks Skykomish River and those above the confluence of the three forks of the Snoqualmie River. The lower drainage comprises the remaining areas downstream.

The upper drainage is formed on mountainous terrain and is characterized by narrow river valleys. Soils in the mountainous parts are variable in depth and texture where they overlie glacial till, and they are shallow and stony where they overlie consolidated rock or glacial outwash. Soils in the narrow river valleys are derived from alluvial materials on flood plains, and are imperfectly drained. Excessive erosion of soils in the upper drainage is limited to a profuse cover of vegetation, except in areas that have been subjected to logging and accompanying road construction. Some erosion of stream channels occurs during periods of high runoff. Sediment transport in the upper drainage areas is small except during periods of high runoff.

Suspended sediment data in the Snoqualmie River system indicate that the South Fork transports more sediment than any of the other forks of the river. On the South Fork Snoqualmie River at North Bend, a representative analysis showed that suspended sediments consisted of 35% clay, 48% silt, and 17% sand. A similar analysis for the Middle Fork Snoqualmie River near Tanner shows 8% clay, 36% silt, and 56% sand.

The lower drainage consists of broad river valleys with adjacent uplands, some of which are formed on mountainous terrain similar to that of the upper drainage. Soils of the uplands are derived from glacial drift and are well drained. In the broad valleys, soils are formed on alluviated flood plains and are generally quite permeable, but some localized valley areas contain poorly drained organic soils. As in the upper drainage, erosion of soils on the steep slopes is small because of dense vegetation, but soils on the flood plains in many areas, where the vegetation has been removed, are subjected to sheet and rill erosion.

Most of the suspended sediment in the lower drainage is transported by the trunk streams, the Snoqualmie and Skykomish Rivers, and then only

during periods of high runoff, a feature characteristic of most streams that discharge to Puget Sound. On the basis of data obtained in 1965 and 1966, the Snoqualmie River transports an estimated 230,000 tons of suspended sediment annually in an average year. Measured concentrations of suspended-sedimen here ranged from 4 to 108 ppm, and the maximun concentration probably is less than 1,000 ppm. Measured sediment concentrations for the North Fork of the Tolt near Carnation have ranged from 1 to 32 ppm. The Skykomish River may transport about 130,000 tons of suspended sediment annually on the average, considerably less than the Snoqualmie. Measured suspended-sediment concentrations on the Skykomish River in 1965 and 1966 ranged from 1 to 28 ppm. Significant transport of bed materials in streams in the lower drainage is evidenced by the occurrence of large bars of gravel and cobbles.

The deposition of sediments in reservoirs in headwater areas will probably be small except during large floods. Changes in sediment transport resulting from man's activities in the upper watershed areas are believed to be only temporary.

GROUND WATER

Ground-water resources in the Snohomish Basin are discussed separately by lowland and mountain areas, because of contrasting geologic environments. The lowlands lie generally west of Sultan, Duvall, Carnation, and Fall City, and the mountains are to the east.

LOWLANDS

Geology and Ground Water Occurrence

The important aquifers in the lowlands are contained in coarse Quaternary sedimentary deposits that are rather continuous over about a 450-square-mile area. The Quaternary deposits are thicker than 2,000 feet locally. However, aquifers capable of furnishing large quantities of fresh water to wells generally do not occur at depths greater than 100 feet below sea level, except where they underlie the Snoqualmie flood plain; there, artesian aquifers are 500 feet or more below sea level.

Quaternary sediments exposed at the surface are mainly till in upland areas and alluvium in river valleys, although till occurs at depth beneath some of the valleys. It is probably absent under most of the flood plain downstream from Snohomish. The till may be as much as 150 feet thick on some higher plateaus, but it is truncated along some plateau margins, and thins to a featheredge over consolidated rocks. Because it is composed largely of compacted fine materials, till is not an important aquifer, even though it is somewhat permeable.

On uplands, the till is overlain by isolated deposits of recessional outwash, which in many places are thin and contain little if any water. In the trough that extends northward from Marysville, as well as on terraces in both the Skykomish Valley and in the Pilchuck River Valley near Granite Falls, recessional outwash is composed mainly of fine sediments 100 feet or less in thickness and is usually saturated to within about 10 feet of the land surface.

Recent alluvium underlies flood plains of the present drainage system and a relict flood plain between Snohomish and Monroe. Alluvium is rather extensive on the Snohomish and Snoqualmie flood plains. It is at least 100 feet thick at the mouth of the Snohomish River and is more than 200 feet thick in many places beneath the Snoqualmie Valley. The alluvium is composed of sand, silt, clay, peat, and minor lenses of gravel. The sediments become coarser in upstream reaches, and thick gravel beds are common at the confluences of trunk streams and mountain tributaries. Alluvium is generally saturated to about river level.

Quaternary sediments older than till are commonly exposed on bluffs that border the Snoqualmie Valley in King county. These older sediments contain sand and gravel aquifers at most places, but the more productive aquifers, commonly more than 100 feet thick, are beneath the terraced area about 5 miles north and east of Monroe and beneath plateaus northwest of Marysville and southwest of the Snohomish River. The aquifers are characteristically confined under artesian pressure except where they occur beneath higher uplands under water-table conditions.

Practically all recharge to the aquifers in the lowlands is by infiltration of precipitation. Aquifers in the lowlands are estimated conservatively to receive an average of about 80,000 acre-feet of recharge annually. Opportunities for induced recharge may exist in some areas along the Pilchuck and

Skykomish Rivers, along the Snohomish River upstream from Snohomish, and at confluences of the Snoqualmie River with the Tolt River and Raging River. Artificial recharge may be feasible on the relict flood plains between Snohomish and Monroe and north of Marysville, although the vertical permeability of the surficial materials there is not now known.

The natural discharge of ground water is mostly into the Snohomish and Snoqualmie Rivers and their tributaries and into Puget Sound through springs that occur above and below the level of tidewater.

Quality of Ground Water

Water in most aquifers is generally low in dissolved solids, and is acceptable for practically all uses. Dissolved-solids content is generally less than 200 ppm and water hardness rarely exceeds 120 ppm. Silica concentrations commonly are in the 20-40 ppm range. Undesirable iron concentrations occur mainly in shallow aquifers beneath poorly drained areas where peaty or boggy soils are present. Saline ground water often occurs in the flood-plain and delta areas downstream from Snohomish, and at some places along the shoreline. Significant salt-water enroachment has not been observed.

Utilization and Development

Ground water pumped in the lowlands is used principally for domestic purposes. Most of the communities in the basin have public-supply systems that use ground water. Irrigation use of ground water is mostly in the Snohomish-Monroe area and in the trough that extends northward from Marysville. Ground water is used for industrial purposes mainly in the Everett area.

Water in alluvium or recessional outwash supplies mostly irrigation wells, of which most are less than 50 feet deep. Wells in uplands and on intermediate terraces are as deep as 200 feet. Most public-supply systems pump water from deeper aquifers below till or clay, but Carnation and Fall City obtain water from springs that emerge from recessional outwash. The largest yielding wells, those used for municipal and industrial supply, generally pump less than 500 gpm; most of them are more thoroughly completed and developed than those used for other purposes. Figure 23 shows order-of-magnitude estimates of expected well yields in the basin. The largest yields are obtainable from wells completed in the aquifers older than till. Only small well yields are obtainable in about a 5-square-mile area north of Lake Stevens and in areas where older consolidated rocks are exposed at the surface. Wells that tap the deeper aquifers beneath valleys may flow.

MOUNTAINS

In the mountainous areas, sand and gravel aquifers are contained in Quaternary glacial drift and alluvial deposits, which, in the aggregate, occupy about 350 square miles. The alluvial deposits occur on flood plains of the Skykomish and Snoqualmie Rivers and their tributaries. Glacial drift occurs both along and beneath the flood plains and throughout a rather extensive area east of the main stem of the Snoqualmie. In areas where Quaternary sediments are absent, ground water is obtainable only from consolidated rocks in which well yields of 10 gpm or less can be expected.

Ground water is used in the mountains principally for domestic supplies. Well yields of as high as 500 gpm have been obtained from water-bearing intervals about 10 feet thick within the alluvium.

The aquifers are recharged by infiltration of precipitation and by infiltration of runoff from the valley slopes upstream from North Bend. The abundance of precipitation suggests relatively large potential recharge.

Moreover, in an area upstream from North Bend, considerable underflow enters the basin from the adjacent Cedar River basin, partly because of seepage from Seattle's reservoirs.

The chemical quality of ground water in the mountain areas is excellent except for localized undesirable iron content in both shallow and deep aquifers.

CEDAR—GREEN BASINS
SURFACE WATER

The Cedar-Green Basins comprise 1,220 square miles, including 1,161 square miles of land and inland water. A map of the basins is shown in Figure 85. This study area consists of two important watersheds, the Lake Washington and the Green-Duwamish basins.

The drainage basin of Lake Washington comprises 607 square miles above the Hiram Chittenden Locks. Within this basin, the two principal tributaries to Lake Washington are the Cedar and Sammamish Rivers. Several minor streams also drain into the lake which, in turn, drains into Puget Sound through the Lake Washington Ship Canal.

The Cedar River has a drainage area of 188 square miles, and heads in a mountainous area where precipitation is abundant. The river is 50 miles long, and flows northwesterly from its source in the Cascade Mountains into Lake Washington at the city of Renton. Chester Morse Lake (formerly called Cedar Lake), 33 miles above the river mouth, provides 52,000 acre-feet of active storage for domestic water supply to the city of Seattle and for power development. Below the power plant the river gradient is 200 feet per mile to the Seattle diversion dam at Landsburg. From Landsburg to Maple Valley, a distance of 18 miles, the river falls at the rate of 37 feet per mile, and from Maple Valley to its mouth the gradient averages 23 feet per mile.

The other main tributary of Lake Washington is Sammamish River, the outlet of Sammamish Lake. The river drains 240 square miles and is 14 miles long. Streams that flow into Sammamish Lake are small, draining foothills below an altitude of 3,000 feet. For that reason, the average discharge of Sammamish River is less than that of Cedar River, even though its drainage basin is larger.

The Green River drains a 483-square-mile area on the west slope of the Cascade Range, and flows westward and northward about 60 miles to Tukwila, where it becomes known as the Duwamish River. The Duwamish flows northward an additional 12 miles and enters Elliott Bay through two outlets, the East and West Waterways.

The upper drainages of the Green River are steep mountainous valleys that contain turbulent streams in forested lands. The river spills forth from the hills onto the outwash plain just above Auburn, and flows about 20 miles to the Duwamish River through a fertile valley 2 to 3 miles wide.

The upper basin of the Green River has been the main watershed for Tacoma's municipal water supply since 1913. Within the watershed, Howard A. Hanson Dam was completed at Eagle Gorge in 1962, providing storage to control floods and to augment the summer low flows downstream.

Downstream from the dam the Green River flows through a 15-mile gorge before emerging into the broad alluvial Green-Duwamish Valley near Auburn. In the gorge, the river receives the flow of numerous springs. Downstream from the gorge the only tributary streams of any size are Newaukum Creek and Big Soos Creek.

The Duwamish River flows through a somewhat narrower valley. A reach of about 5 miles of the lower Duwamish River has been improved for navigation.

Prior to 1906, the Duwamish River received the waters of the Green, White, and Black Rivers. In that year, flow in the White River was permanently diverted into the adjacent Puyallup basin, leaving only the Green River to flow northward from Auburn to its confluence with the Black River. In 1916, the Black River lost its identity as the outlet of Lake Washington when the Lake Washington Ship Canal was completed and the level of the lake was lowered about 9 feet. Thus, the major changes of 1906 and 1916 reduced the Duwamish River basin to a fourth of its former size.

STREAMFLOW

Runoff Characteristics

Data obtained in the Cedar-Green Basins indicate a range in mean annual runoff contribution from about 100 inches near the Cascade crest in the Cedar River basin to less than 20 inches near Seattle. As an annual average for the 1,161 square miles of land and inland water in this basin, estimated runoff for the 30-year standard period (1931-60) was about 36 inches, or 2,200,000 acre-feet.

One of the longest periods of streamflow history in the Puget Sound area is provided by the record obtained at the Cedar River gaging station near Landsburg. In the period during which this station

has been operating, the actual gage location has been changed several times. However, with the exception of a little more than 2 years near the turn of the centruy and a few months in 1913 and 1914, continuous measurements have been made at this site since 1895. These data represent the runoff contribution from approximately the upper half of the Cedar River basin with the exception of a few upstream diversions and some regulation by Chester Morse Lake. During 1931-60, flow measurements at these sites indicated an average annual discharge of 680 cfs or a yield of 493,000 acre-feet per year. This equates to a unit discharge and yield of 5.8 cfs per square mile, which is slightly more than that for the upper half of the adjacent Green River watershed.

Because the Cedar River drainage is more or less centrally located within the Puget Sound Study Area, its annual runoff variations are quite representative of trends throughout the Study Area. Figure 73, therefore, provides an excellent picture of general long-term runoff conditions for the region since 1896. Occasionally, groups of several consecutive yearly discharges tend to be either greatly above or below the normal, but there is no consistent pattern to these tendencies; instead they seem to occur at random intervals.

Natural runoff from the upper part of the Green River watershed has been measured since 1932 at a station near the community of Palmer. This site is above the City of Tacoma diversion dam and water-supply intake, so the records do not reflect any significant diversions. Although Howard Hanson flood-control dam is now situated above the station, the records collected during 1931-60 were not affected by this project. Adjusted for 1 year of missing data, the standard 30-year mean streamflow of the Green River basin above the Palmer gage is 1,080 cfs, or 784,000 acre-feet per year. For each square mile of the drainage area, the mean annual yeild is 4.7 cfs.

As shown in Figure 74, the maximum annual runoff of record at this site occurred during water year 1959. In this peak year, the flow averaged 139%

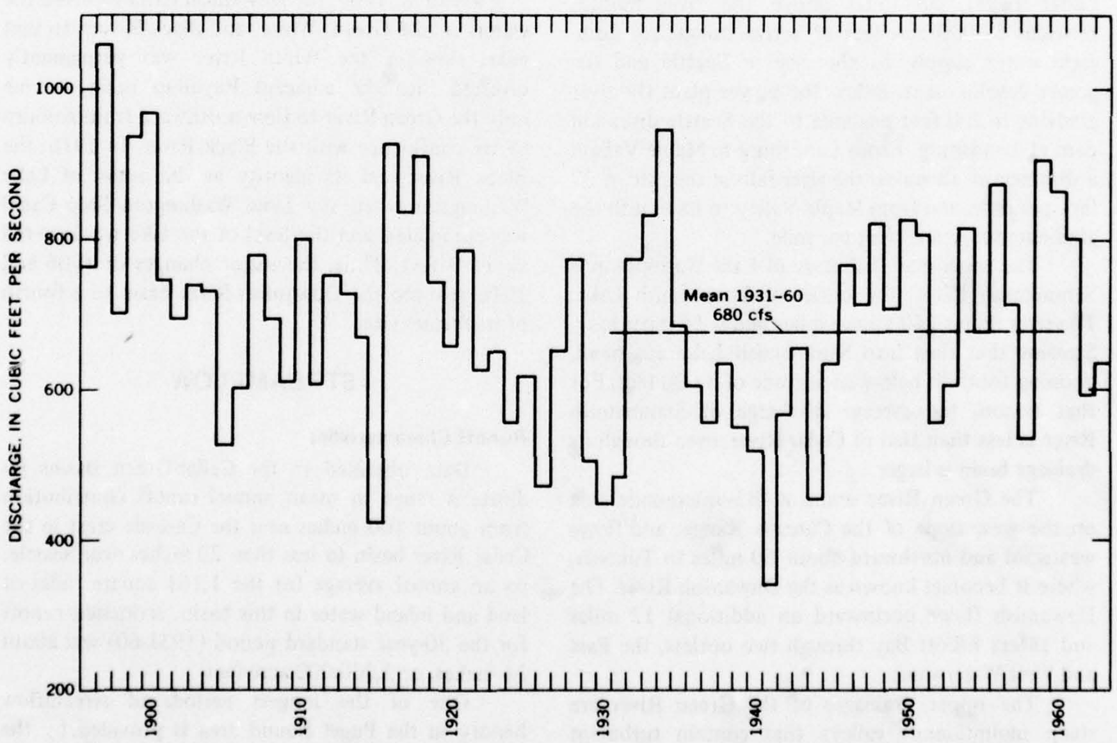


FIGURE 73.—Annual discharges, Cedar River near Landsburg.

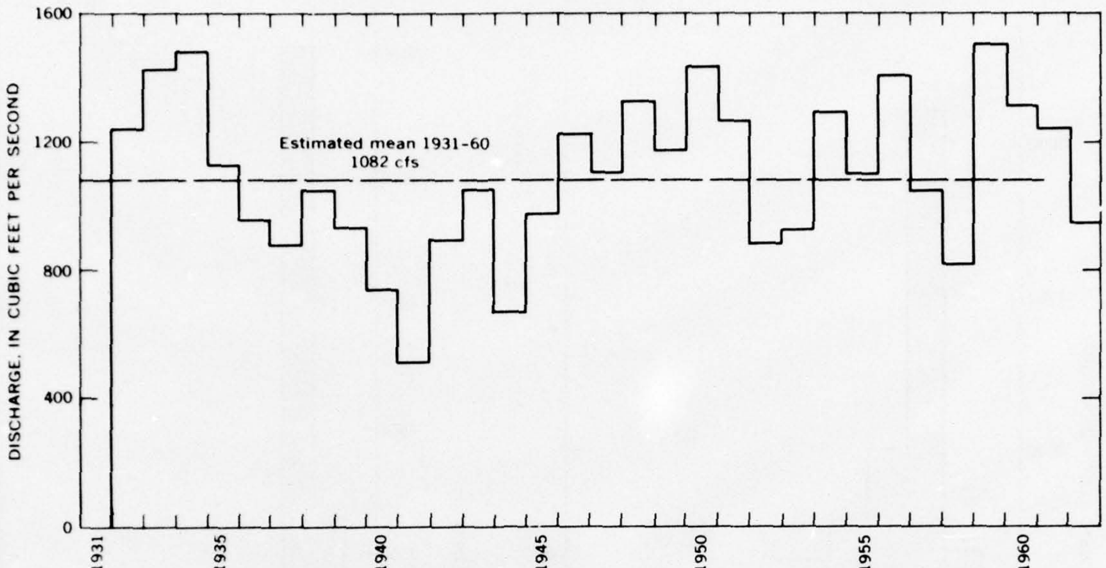


FIGURE 74.—Annual discharges, Green River near Palmer.

of the 30-year mean discharge. The minimum yearly flow of record, which occurred in 1941, amounted to 47% of the 30-year mean.

The bar chart of mean monthly flows for the Cedar River near Landsburg (Figure 75) is typical of the seasonal runoff pattern displayed by other primarily rain and snow-fed streams in western Washington. The highest flows normally occur from direct runoff during December and January. These winter flows recede slightly as spring approaches, and then merge into the less pronounced snowmelt runoff peak during April, May, and June. Snowmelt contributes a slightly lower percentage to runoff in the Cedar River Basin than in adjacent stream systems.

The base flows during the dry summer season are relatively high, in part because of the storage influence of Chester Morse Lake and the sizable ground-water contributions from storage in the lowlands above the Landsburg gage.

Monthly flow characteristics of the Green River, based on records obtained at the gaging station near Palmer, are depicted in Figure 76. Generally two periods of high flow occur each year. The greater discharges usually result from winter rains, whereas somewhat lower peaks occur in April and May from snowmelt and spring rains. Snow storage seems more influential in the Green River watershed than in the Cedar drainage, but less influential than in the White River basin.

After snowpacks have dissipated, flows in the Green River recede rapidly, and normally reach a minimum during August. The unusually small minimum flows of this stream reflect the absence of storage in glacial ice and the meager contribution from ground-water above the Palmer gage. Because of the major diversion of the City of Tacoma, base-flow conditions do not improve appreciably in the lowlands below this location.

Seasonal runoff patterns in the Sammamish River drainage are comparable to those other rain-fed streams of the Puget Sound lowlands. The Sammamish River stream-gaging site at Bothell measures runoff from 88% of the basin. Streamflow at this site is primarily dependent on the amount of outflow from Lake Sammamish, which receives 40% of the basin runoff. The Sammamish streamflow usually begins to increase in September from the summer base flow of about 200 cfs. Streamflow during October-March is characterized by a series of sharp rises superimposed on a base flow. Runoff decreases from March to September as a result of reduced precipitation. The variability of the daily flow of streams in the Cedar-Green Basin is presented as flow-duration data for selected gaging Stations in Table 33.

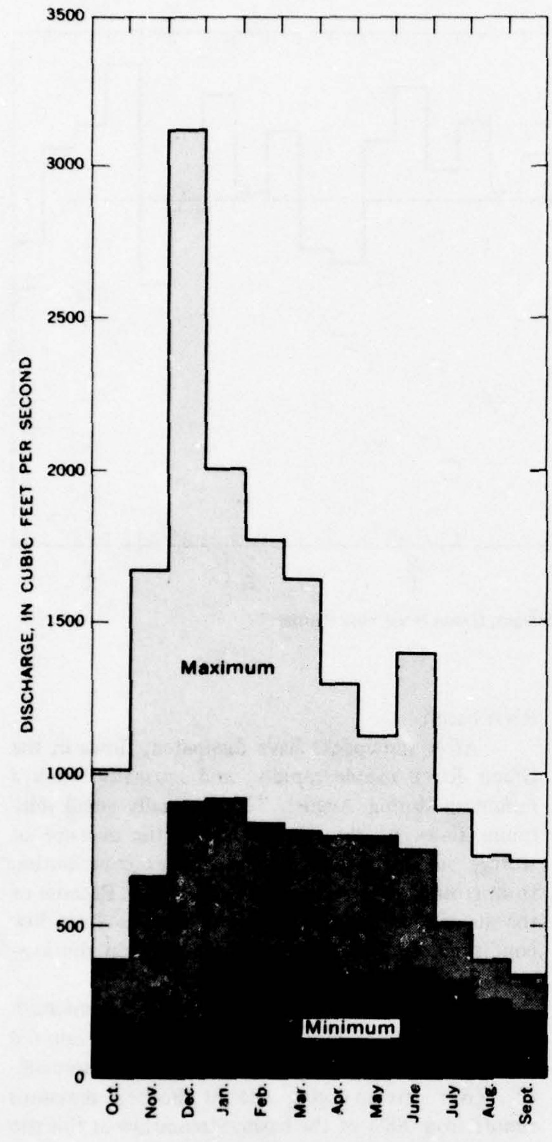


FIGURE 75.—Maximum, mean and minimum monthly discharges, Cedar River near Landsburg, 1931-60.

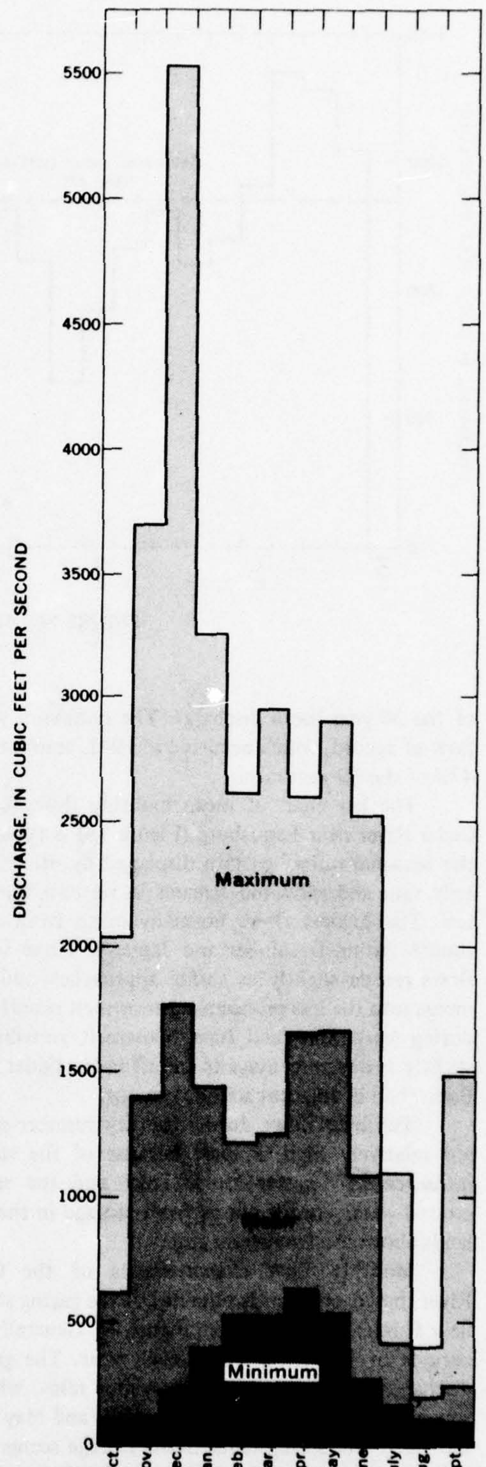


FIGURE 76.—Maximum, mean and minimum monthly discharges, Green River near Palmer, 1931-60.

TABLE 33.—Flow-duration data for selected gaging stations in the Cedar-Green Basins

Gaging station	Period of Analysis	Flow, in cubic feet per second, which was equaled or exceeded for indicated percent of time											
		99	95	90	80	70	50	30	20	10	5	1	0.1
Snow Creek near Lester	1946-64	4.5	6.4	8.2	13.5	21	42	78	109	160	215	390	780
Friday Creek near Lester	1946-64	2.1	3.0	4.0	6.4	9.8	18	32	44	64	84	141	265
Green River near Lester	1946-64	30	40	51	85	139	275	475	640	940	1,300	2,400	5,000
Smay Creek near Lester	1947-64	5.8	8.0	10	15	22.5	39	61	78	110	140	240	510
Charley Creek near Eagle Gorge	1947-55	9.0	12	15	22	31	53	85	108	146	195	360	730
North Fork Green River near Palmer	1957-64	2.8	7.8	11.5	21	35	67	105	135	190	260	470	930
Bear Creek near Eagle Gorge	1947-55	.95	1.8	2.9	5.4	8.4	16.5	29.5	40	58	78	160	410
Green River near Palmer	1932-58	104	130	160	235	380	760	1,280	1,650	2,280	2,900	5,500	13,000
Green River near Black Diamond	1940-48	81	110	140	225	380	750	1,210	1,540	2,150	2,800	4,650	10,500
Newaukum Creek near Black Diamond	1945-61	11	16	19	23	28	47	75	94	131	182	360	730
Covington Creek near Black Diamond	1954-59	0	0	0	.2	3.1	18	37	49	66	83	125	190
Big Soos Creek near Auburn	1945-55	22.5	27	30	36	44	84	145	185	250	315	480	700
Green River near Auburn	1937-61	120	161	200	300	520	1,080	1,690	2,070	2,720	3,460	6,100	13,000
North Fork Cedar River near Lester	1945-63	7.3	10	13	18	24	42	79	113	170	225	375	710
South Fork Cedar River near Lester	1945-64	2.8	4.0	5.4	8.5	12.5	24	44	62	94	130	232	450
Cedar River below Bear Creek near Cedar Falls	1946-63	17.5	22.5	32	47	67	119	209	282	410	540	870	1,500
Cedar River near Cedar Falls	1946-64	27	38	49	77	115	205	325	425	595	770	1,300	2,800
Rex River near Cedar Falls	1946-65	6.6	10	14	25	38	73	122	160	225	300	570	1,300
Taylor Creek near Selleck	1957-64	18.5	23.5	29	40	56	93	130	154	190	233	380	820
Cedar River near Landsburg	1897-61	175	240	278	345	420	600	800	930	1,140	1,370	2,400	5,000
Rock Creek at Highway 5A near Ravensdale	1957-62	3.7	5.0	5.8	7.0	8.5	12	21	27	34	41	70	120
Rock Creek near Maple Valley	1946-61	3.9	5.2	6.1	7.5	9.2	16	27	35	47	59	92	145
May Creek near Renton	1946-50	2.0	2.4	2.8	3.4	4.3	11	24	35	54	74	130	250
Mercer Creek near Bellevue	1956-61	3.2	4.1	4.8	6.0	7.7	15	24	32	47	64	110	210
Issaquah Creek near Issaquah	1946-64	12.5	15	17	21	27	47	80	105	150	200	340	640
Bear Creek near Redmond	1946-49	4.8	5.8	6.7	8.4	10.5	20.5	35	47	66	85	125	170
Cottage Lake Creek near Redmond	1956-61	4.2	4.9	5.4	6.3	7.4	11	16	20	28	38	64	130
Evans Creek above mouth near Redmond	1956-64	6.2	7.0	7.7	8.9	10.5	16	26	33	45	56	87	150
Sammamish River near Redmond	1940-56	53	63	72	92	120	215	380	475	610	720	1,000	1,400
North Creek near Bothell	1946-60	5.6	6.4	7.2	8.8	11	21.5	41	56	83	113	200	350
Sammamish River at Bothell	1940-63	74	88	100	125	160	270	470	580	760	920	1,280	1,700

Flood Characteristics

Floods on the Sammamish River are characterized by sharp rises, followed by recessions almost as rapid; this pattern is superimposed on the high base flow that is maintained by outflow from Lake Sammamish. Flood characteristics at the Bothell gaging site have changed since 1964 as a result of an improved channel capacity in the Sammamish River and a new outlet at the Lake. The improvements provide a higher winter base flow in the river and reduction of high stages on Lake Sammamish.

Floods in the Cedar and Green River basins are caused by high rainfall with accompanying snowmelt. Two or more flood peaks often occur within 2 weeks. In the Cedar River basin, Chester Morse Lake reduces the peak discharge per square mile of drainage area. The maximum peak discharge during the period of record on the Cedar River at Renton occurred on February 11, 1951. Though no record of discharge was obtained, the discharge on this date is estimated to have been about 7,000 cfs. The maximum discharge recorded on the Green River near Auburn was 28,100 cfs on November 23, 1959. Howard A. Hansen Dam, a Corps of Engineers flood control project, 32 miles above the Auburn gage, has effectively reduced the magnitude of large floods since March 1962. Storage at the dam results in a lower-than-natural base flow during the period April-May, while the reservoir is filling, and a higher-than-natural base flow during June to October or November as the pool is drained.

Flood-frequency curves for Sammamish River at Bothell, Cedar River at Renton, and Green River near Auburn are presented in Figures 77-79. The period of record at these sites is as follows: Sammamish River at Bothell, 1940-63; Cedar River at Renton, 1946-64; Green River near Auburn, 1937-64. Frequency statistics were extended to a longer period by correlation with records on the South Fork Skykomish River near Index, which has a 54-year record. The extended periods of record for the sites in the Cedar-Green Basins are as follows: Sammamish River at Bothell, 30 years; Cedar River at Renton, 27 years; Green River near Auburn, 40 years.

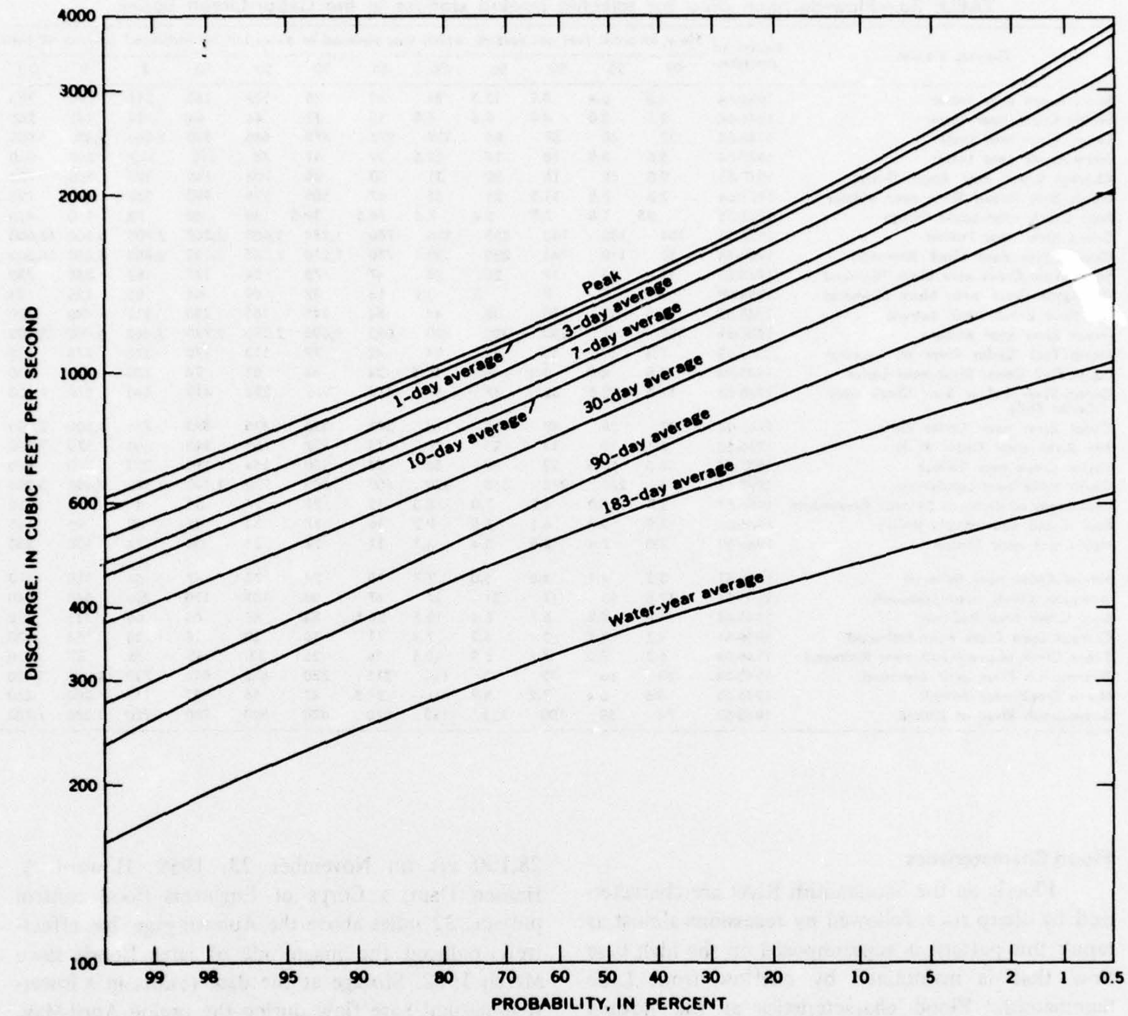


FIGURE 77.—*Probability curves of annual maximum flows for specified time periods, Sammamish River at Bothell.*

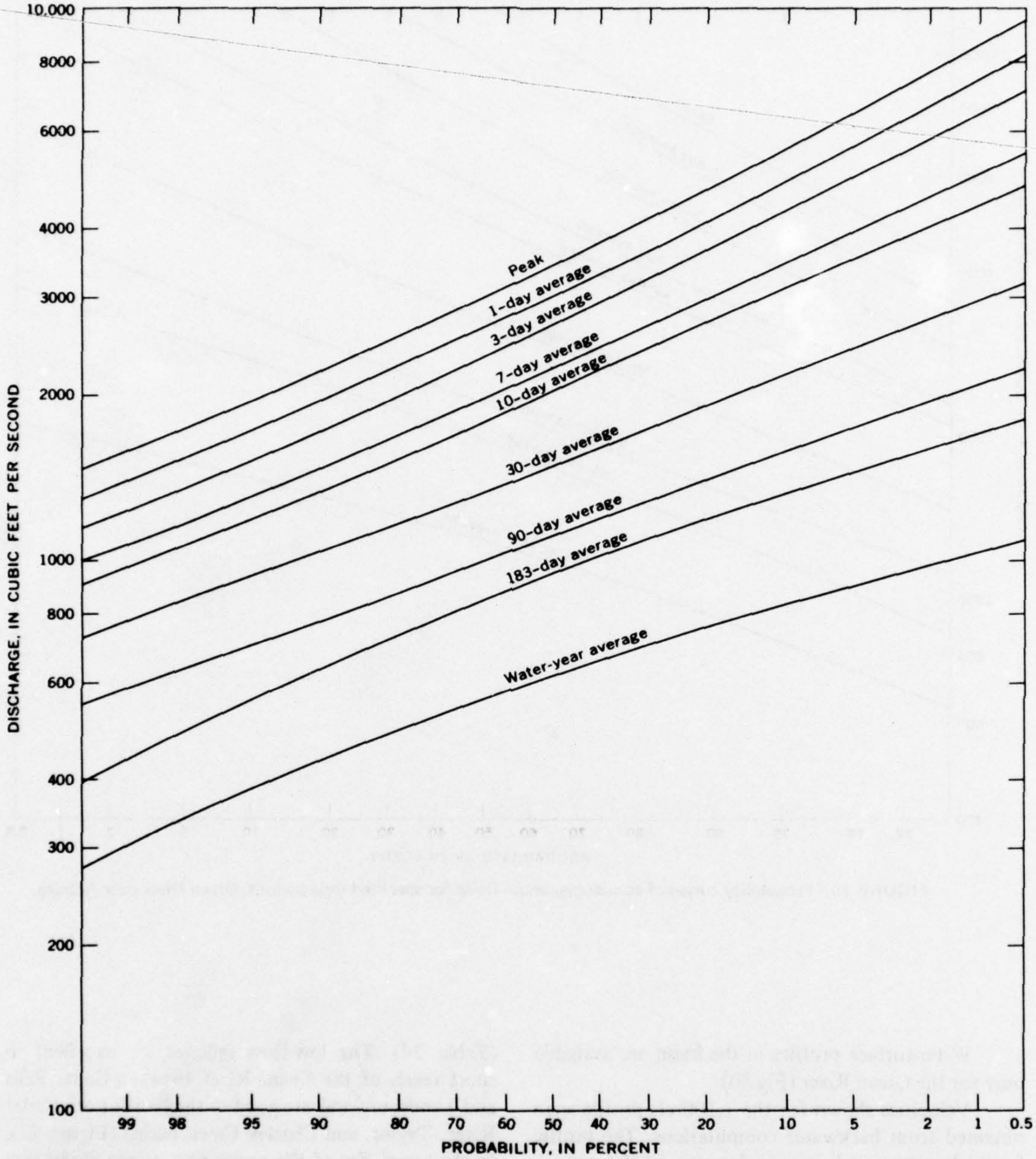


FIGURE 78.—Probability curves of annual maximum flows for specified time periods, Cedar River at Renton.

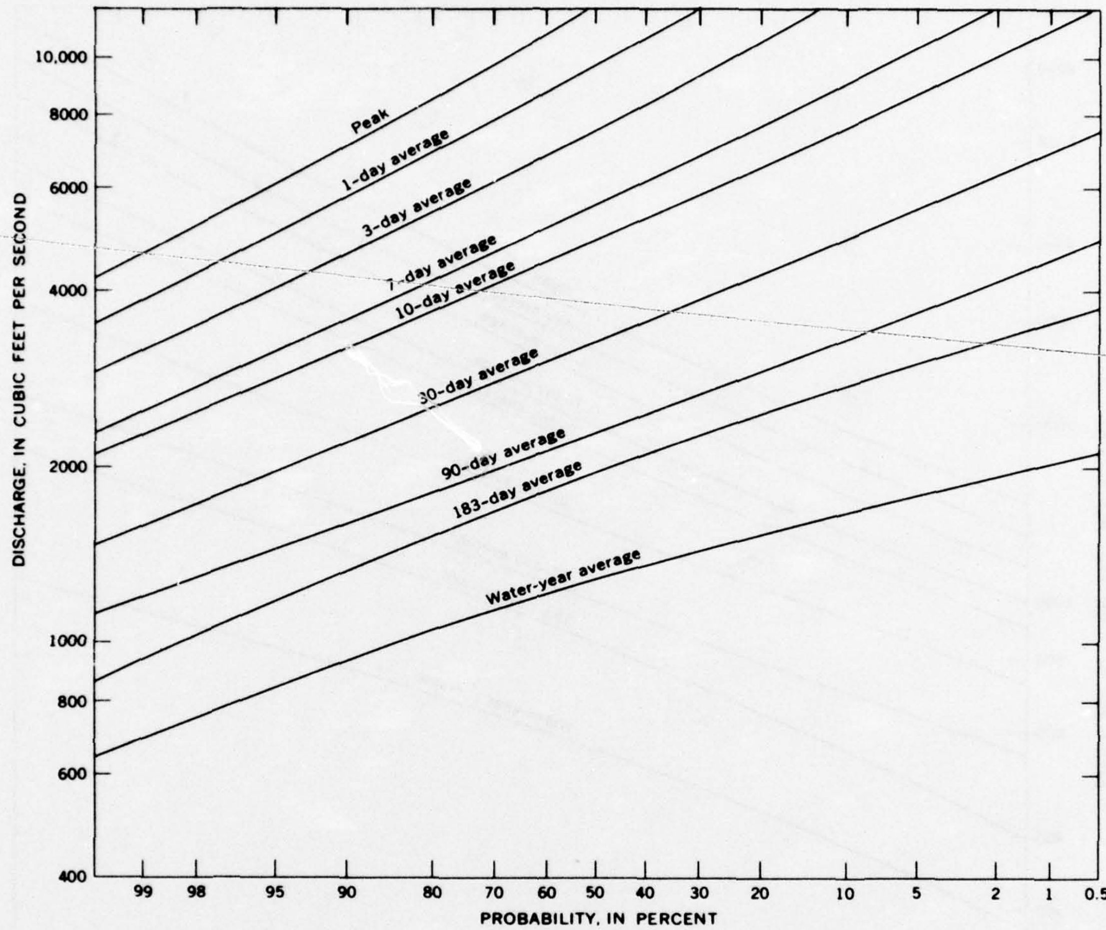


FIGURE 79.—Probability curves of annual maximum flows for specified time periods, Green River near Auburn.

Water-surface profiles in the basin are available only for the Green River (Fig.80).

Velocities shown for the 1,100 cfs profile were obtained from backwater computations. The profile for high-water conditions in January 1965 approximates bankfull stages. The Green River has no abrupt changes in gradient between the mouth and river mile 31.

Low-Flow Characteristics

Low-flow characteristics of streams in the Cedar-Green Basins are compared using indexes from low-flow frequency curves at 35 gaging stations (Table 34). The low-flow indexes are excellent in short reach of the Cedar River between Cedar Falls and Landsburg and are good in the North Fork Cedar River, Taylor, and Charley Creek basins (Figure 22). In the remainder of the upper part of the study area the low-flow indexes are fair. As in other study areas, the low-lying streams in the areas adjacent to Puget Sound have poor values. In general, the slope and spacing indexes, which show the variability of low flows is greater in streams draining the higher altitudes in the basins. The streams that are tributary to Lake Washington and Sammamish Lake have less variability from year to year during low-flow periods.

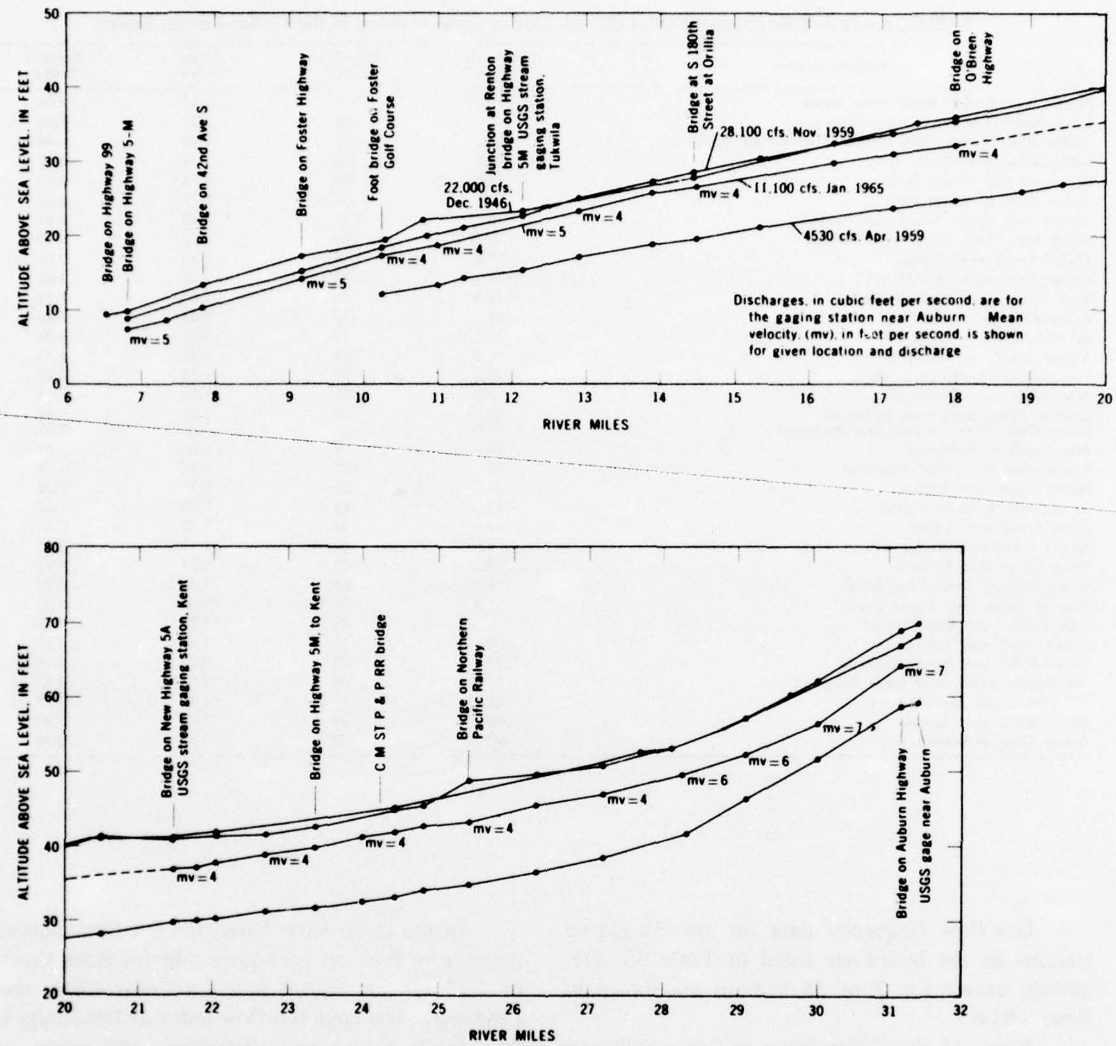


FIGURE 80.—Water-surface profile of Green-Duwamish River, mile 6.55-32.

TABLE 34.—Low-flow characteristics for selected gaging stations in the Cedar-Green Basins

Gaging station	Drainage area	Low-flow index	Slope index	Spacing index
North Fork Cedar River near Lester	9.30	1.11	1.64	4.06
South Fork Cedar River near Lester	6.00	.68	1.96	5.50
Cedar River below Bear Creek near Cedar Falls	25.4	.95	1.69	4.46
Cedar River near Cedar Falls	40.7	.88	1.64	4.67
Rex River near Cedar Falls	13.4	.69	1.75	6.73
Cedar River at Cedar Falls	84.2	.52	3.78	4.09
Middle Fork Taylor Creek near Selleck	5.17	1.41	1.82	2.81
North Fork Taylor Creek near Selleck	3.77	.56	3.70	6.19
Taylor Creek near Selleck	17.2	1.37	1.47	2.81
Cedar River near Landsburg	117	2.22	1.52	1.81
Rock Creek near Maple Valley	12.6	.44	1.85	1.72
Cedar River at Renton	186	.54	3.45	3.66
May Creek near Renton	12.5	.19	1.41	1.96
Mercer Creek near Bellevue	12.0	.32	1.35	2.11
Issaquah Creek near Issaquah	27.0	.56	1.35	1.93
Bear Creek near Redmond	13.9	.36	1.39	1.96
Cottage Lake Creek near Redmond	10.7	.45	1.22	1.50
Evans Creek above mouth near Redmond	13.0	.51	1.22	1.52
Bear Creek at Redmond	48.2	.39	1.16	1.83
Sammamish River near Redmond	150	.47	1.52	1.79
North Creek near Bothell	24.6	.25	1.27	2.03
Sammamish River at Bothell	212.	.45	1.45	1.69
Snow Creek near Lester	11.5	.54	1.72	5.65
Friday Creek near Lester	4.67	.62	2.13	5.18
Green River near Lester	96.2	.40	1.54	5.27
Green Canyon Creek near Lester	8.56	.96	1.64	3.72
Charley Creek near Eagle Gorge	11.3	1.06	1.52	3.33
Bear Creek near Eagle Gorge	4.10	.43	1.79	6.59
Green River near Palmer	230	.65	1.49	3.87
Green River near Black Diamond	285	.39	2.22	5.00
Newaukum Creek near Black Diamond	27.4	.59	1.61	1.82
Big Soos Creek near Auburn	59.2	.51	1.49	1.57
Green River near Auburn	399	.44	1,96	3.81
Green River at Tukwila	440	.50	1.82	3.50

Low-flow frequency data for the 35 gaging stations in the basins are listed in Table 35. Frequency curves for 3 of 35 stations are shown in Figures 81-83.

Flows of the Cedar River at Cedar Falls and Landsburg are affected by regulation for power development at Chester Morse Lake and Masonry Pool. Upstream regulation and diversion for municipal use by Seattle affect the records of Cedar River at Renton. Recent channel improvements may change the low-flow characteristics of the Sammamish River. The Green River below Palmer is affected by diversion to Tacoma and, since 1962, by operation of Howard A. Hanson Dam for flood control. Therefore, the low-flow characteristics determined for the Green River below Palmer are not representative of present day and future flows. There are small diversions for domestic use, but discharge records for the remaining streams are nonetheless considered to represent essentially natural flow conditions.

In the Cedar River basin, the low-flow indexes range from 0.44 cfs per square mile for Rock Creek to 2.22 cfs per square mile for Cedar River near Landsburg. The large low-flow index at Landsburg is due partly to upstream regulation and partly to seepage from Chester Morse Lake and Masonry Pool. Taylor Creek has an index of 1.37 cfs per square mile, which results from large ground-water contributions in the unconsolidated alluvial and outwash sediments underlying the basin. The low-flow indexes of other streams tributary to Lake Washington are uniform, and range from 0.19 cfs per square mile for Mary Creek to 0.56 cfs per square mile for Issaquah Creek. Rather small contributions from ground-water storage may account for these small indexes.

In the Green River basin, low-flow indexes range from 0.39 cfs per square mile for Green River near Black Diamond to 1.06 cfs per square mile for Charley Creek. The low-flow index for the Green River main stem increases from 0.40 cfs per square

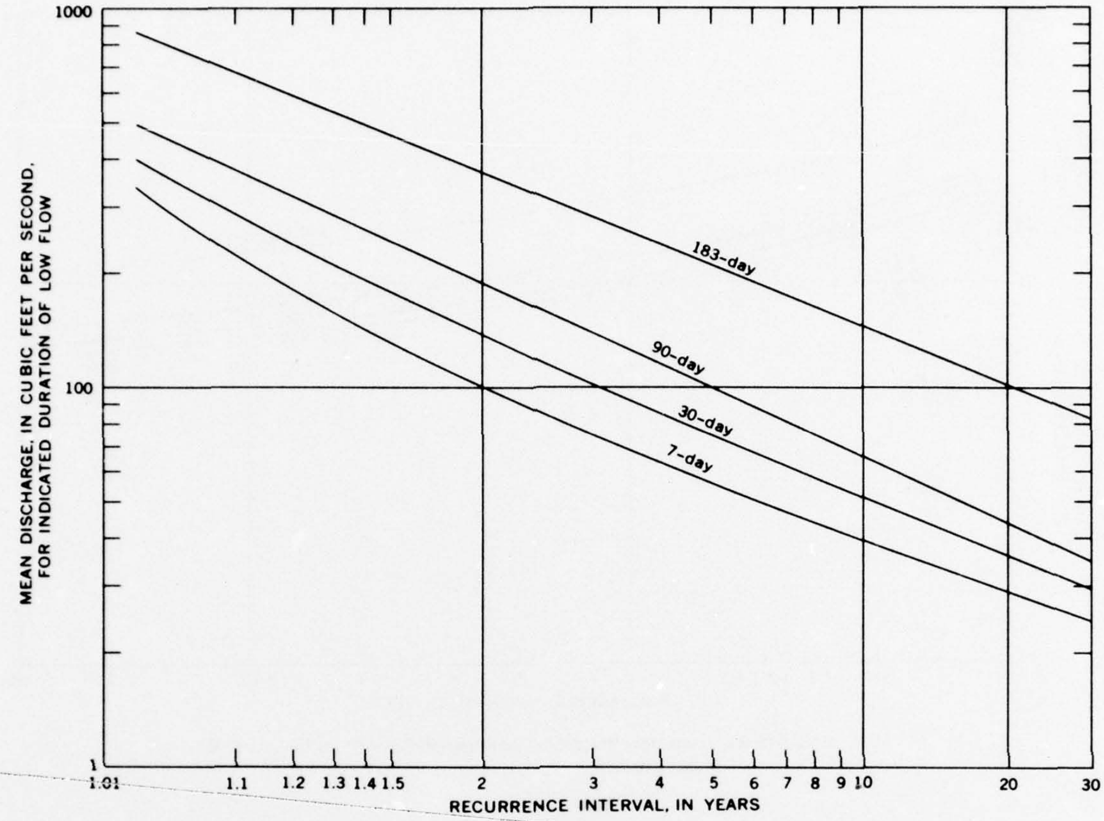


FIGURE 81.—Low-flow frequency, Cedar River at Renton, 1946-63.

mile near Lester to 0.65 cfs per square mile near Palmer and then decreases to 0.39 cfs per square mile near Black Diamond. Below Black Diamond, the index increases to 0.44 near Auburn and 0.50 at Tukwila. The increase between Lester and Palmer is due to contribution from ground-water storage in the alluvium and recessional outwash of the North Fork Green River basin. The decrease in index between Palmer and Black Diamond is a result of Tacoma's diversion. Downstream from Black Diamond, aquifers contained in the sediments of the broad flood plain contribute an appreciable amount of ground-water. Indexes of tributaries to the Green River are fairly uniform, ranging from 0.40 to 0.62 cfs per square mile, except for Smay and Charley Creeks, which have values of 0.96 and 1.06 cfs per square mile, respectively.

Slope indexes in the Cedar River basin range from 1.16 for Bear Creek at Redmond to 3.78 for Cedar River at Cedar Falls. The value for Bear Creek is the lowest determined in the entire Puget Sound Area. All streams draining the low-lying area adjacent to Lake Washington have extremely low values possibly because of the extensive aquifers in the area. The high slope index for the Cedar Falls station shows the influence of regulation and underflow past the station

Slope increases in the Green River basin do not range as widely as those in the Cedar basin. The values range from 1.49 for Big Soos Creek and Green River near Palmer to 2.22 for Green River near Black Diamond. On the main stem, values decrease from 1.54 near Lester to 1.49 near Palmer and then increase to 2.22 near Black Diamond. Below Black

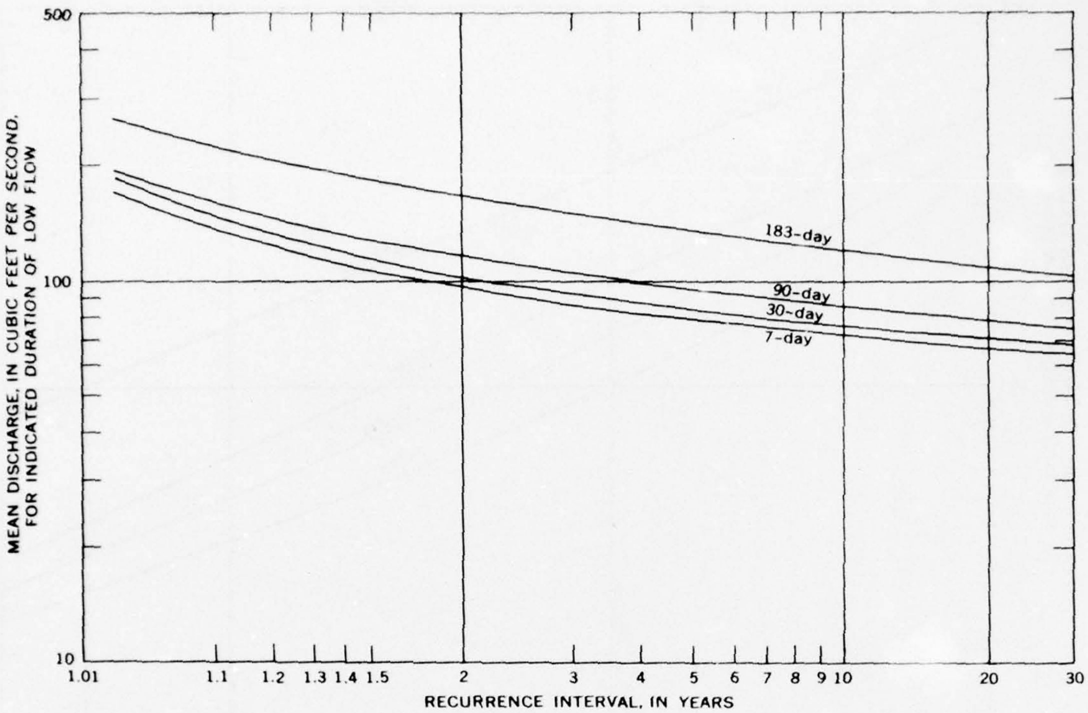


FIGURE 82.—Low-flow frequency, Sammamish River at Bothell, 1946-63.

Diamond, the slope index decreases to 1.96 and 1.82 at Auburn and Tukwila, respectively. The low slope index for Big Soos Creek reflects well-sustained flows from ground-water contributions.

Spacing indexes in the Cedar River basin range from 1.50 for Cottage Lake Creek to 6.73 for Rex River. The value for Cottage Lake Creek is low because the local deposits of unconsolidated sediments are conducive to infiltration of precipitation. The wide spacing between the frequency curves for the Rex River indicates the impervious nature of the geologic materials in the basin.

In the Green River basin, spacing indexes range from 1.57 for Big Soos Creek to 6.57 for Bear Creek. As in the Cedar River basin, the dominant influencing factor is the nature of surface materials in the watershed.

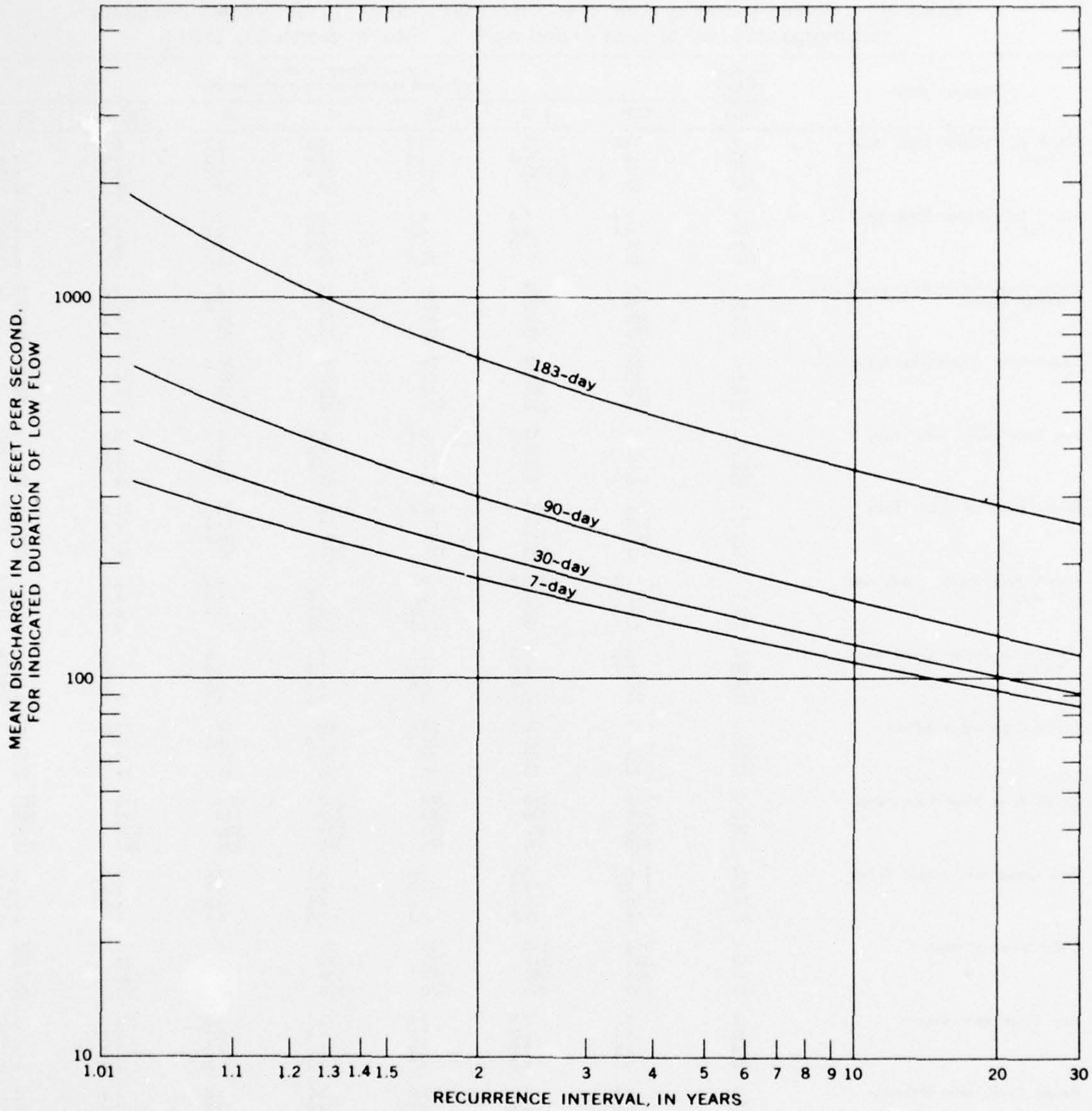


FIGURE 83.—Low-flow frequency, Green River near Auburn, 1946-63.

TABLE 35.—Low-flow frequency data for selected gaging stations in the Cedar-Green Basins
[Discharge adjusted to base period April 1, 1946, to March 31, 1964]

Gaging station	Number of consecutive days	Streamflows in cfs, for indicated recurrence intervals, in years						
		1.05	1.30	2.0	5	10	20	30
North Fork Cedar River near Lester	7	14.5	12	10.3	8.2	7.2	6.3	5.8
	30	18	14.3	11.8	9.0	7.8	6.8	6.3
	90	37	23	16.4	11.4	9.6	8.5	7.9
	183	83	56	42	29	24	20	18.5
South Fork Cedar River near Lester	7	7.8	5.4	4.1	2.9	2.4	2.1	1.9
	30	9.8	6.5	4.7	3.3	2.7	2.3	2.1
	90	22	11.8	7.4	4.4	3.4	2.7	2.4
	183	46	31.5	22.5	14	10.6	8.1	6.9
Cedar River below Bear Creek near Cedar Falls	7	42	30	24	18	16	14.2	13.5
	30	54	36	27	20	17.5	15.8	15
	90	104	61	42	28	23	19.5	18
	183	195	140	107	71	55	44	38
Cedar River near Cedar Falls	7	66	47	36	28	24.5	22	21
	30	82	55	41	31	27	25	24
	90	170	95	63	42	35	31	29
	183	310	220	168	110	88	70	62
Rex River near Cedar Falls	7	19.5	12.5	9.2	6.7	5.8	5.2	5.0
	30	29	16.5	11.3	7.8	6.7	5.9	5.6
	90	59	32	21	12.7	9.7	7.8	7.0
	183	140	86	62	43	37	32	30
Cedar River at Cedar Falls	7	96	65	43.5	24	16.5	11.5	9.3
	30	148	92	61	34	23.3	16.5	13.5
	90	242	142	88	49	38.5	31.5	29
	183	455	280	178	101	80	68	63
Middle Fork Taylor Creek near Selleck	7	18.5	10.7	7.3	5.1	4.4	4.0	3.8
	30	23.5	13.	8.6	5.8	4.8	4.3	4.0
	90	29	16	10.6	6.8	5.4	4.6	4.2
	183	45	29	20.5	13.8	11	9.2	8.4
North Fork Taylor Creek near Selleck	7	5.8	3.3	2.1	1.1	.8	.6	.5
	30	7.7	4.4	2.7	1.5	1.0	.8	.6
	90	13	7.8	4.8	2.4	1.6	1.2	1.0
	183	27	18.5	13	7.6	5.3	3.8	3.2
Taylor Creek near Selleck	7	37	28.5	23.5	19	17	15.8	15
	30	44	33	26.5	21.5	19.3	18	17
	90	68	47	36	26.5	22	19.2	18
	183	110	85	66	46	36	29	26
Cedar River near Landsburg	7	410	310	260	210	184	170	160
	30	460	360	295	235	210	190	180
	90	550	420	335	265	230	210	200
	183	830	600	470	360	320	285	270
Rock Creek near Maple Valley	7	8.2	6.6	5.4	4.1	3.4	2.9	2.6
	30	9.0	7.3	6.0	4.6	3.9	3.4	3.1
	90	10	8.1	6.8	5.3	4.6	4.0	3.7
	183	15	11.7	9.3	7.0	5.8	4.9	4.5
Cedar River at Renton	7	265	158	101	56	40	29	24
	30	330	210	138	75	52	36	30
	90	425	280	187	100	66	44	35
	183	760	530	370	210	148	103	85
May Creek near Renton	7	3.1	2.7	2.4	2.1	1.8	1.7	1.6
	30	4.1	3.2	2.8	2.4	2.1	1.9	1.8
	90	5.2	3.9	3.2	2.6	2.2	2.0	1.9
	183	8.5	6.0	4.7	3.3	2.8	2.4	2.2
Mercer Creek near Bellevue	7	5.6	4.5	3.8	3.2	3.0	2.8	2.7
	30	7.4	5.6	4.7	4.0	3.6	3.4	3.3
	90	8.8	6.6	5.4	4.4	4.0	3.7	3.6
	183	12.7	9.5	8.0	6.4	5.5	5.0	4.6
Issaquah Creek near Issaquah	7	21.5	17.3	15	12.6	11.7	11	10.7
	30	23	19	16.5	14	12.7	11.7	11.2
	90	29	23	19	15.5	14	12.7	12
	183	46	36	29	21	18	15	13.5
Bear Creek near Redmond	7	7.4	5.9	5.0	4.2	3.8	3.6	3.4
	30	8.3	6.5	5.5	4.6	4.1	3.9	3.7
	90	10.3	8.0	6.6	5.2	4.6	4.2	3.9
	183	18.5	13	9.8	7.0	5.9	5.1	4.7
Cottage Lake Creek near Redmond	7	6.7	5.5	4.8	4.2	4.0	3.9	3.8
	30	7.4	6.1	5.4	4.7	4.4	4.2	4.1
	90	8.3	6.7	5.8	5.0	4.7	4.5	4.3
	183	9.7	8.2	7.2	6.0	5.4	4.9	4.7
Evans Creek above mouth near Redmond	7	8.0	7.1	6.6	6.0	5.7	5.4	5.3
	30	8.9	7.8	7.0	6.4	6.2	6.0	5.8
	90	10.2	8.8	8.0	7.1	6.8	6.6	6.4
	183	13.2	11.3	10	8.6	7.9	7.4	7.1

TABLE 35.—Continued

Gaging station	Number of consecutive days	Streamflows in cfs, for indicated recurrence intervals, in years						
		1.05	1.30	2.0	5	10	20	30
Bear Creek at Redmond	7	27	21	18.6	17	16.5	16	15.7
	30	31	23	20.2	18.5	17.8	17	16.6
	90	35	28	24	21.5	20.3	19.5	19
	183	48	39	34	28	26	24	23
Sammamish River near Redmond	7	120	88	70	55	49	46	44
	30	130	94	74	59	53	48	46
	90	160	110	85	67	60	55	53
	183	195	153	125	97	83	73	67
North Creek near Bothell	7	8.7	7.2	6.2	5.4	5.2	4.9	4.8
	30	10	8.0	7.0	6.0	5.6	5.3	5.2
	90	11.7	9.6	8.3	7.2	6.7	6.4	6.2
	183	19.2	15	12.6	10.2	9.0	8.3	7.9
Sammamish River at Bothell	7	150	115	96	78	72	66	63
	30	162	123	102	83	75	70	67
	90	172	135	113	93	84	77	74
	183	240	194	162	130	118	107	100
Snow Creek near Lester	7	10	7.6	6.2	4.7	4.1	3.6	3.3
	30	11.5	8.8	7.2	5.4	4.7	4.0	3.7
	90	30	18	11.9	7.4	6.0	4.9	4.4
	183	68	49	35	21	15.5	11.3	9.6
Friday Creek near Lester	7	5.7	4.0	2.9	1.9	1.6	1.4	1.3
	30	6.8	4.7	3.5	2.5	2.1	1.8	1.7
	90	12	7.6	5.4	3.4	2.7	2.2	2.0
	183	31	21	15	9.4	7.1	5.6	4.8
Green River near Lester	7	64	47	38	30	27	24.7	23.5
	30	74	56	44	34	30	26.5	25
	90	155	93	65	45	38	33	31
	183	430	290	200	120	86	63	53
Green Canyon Creek near Lester	7	3.2	2.4	2.0	1.6	1.4	1.2	1.2
	30	3.6	2.7	2.2	1.8	1.5	1.4	1.3
	90	6.0	4.1	3.1	2.2	1.8	1.5	1.4
	183	11.4	8.4	6.4	4.4	3.4	2.8	2.4
Smay Creek near Lester	7	13.4	10.2	8.2	6.4	5.6	5.0	4.7
	30	16	11.7	9.1	7.0	6.2	5.6	5.3
	90	27.5	17.2	12.5	8.9	7.6	6.6	6.2
	183	59	41	30.5	20	15.8	12.5	11
Charley Creek near Eagle Gorge	7	17	14	12	9.9	8.8	7.9	7.4
	30	24	16.8	14	11.1	9.9	8.9	8.3
	90	36	24	18	13	11.1	9.9	9.3
	183	73	53	40	27	21.5	17.5	15.5
Bear Creek near Eagle Gorge	7	3.7	2.4	1.8	1.3	1.1	1.0	.9
	30	4.8	3.1	2.2	1.6	1.3	1.1	1.0
	90	9.3	5.9	4.1	2.6	2.0	1.6	1.4
	183	22	15.5	11.2	7.3	5.5	4.2	3.6
Green River near Palmer	7	260	190	150	120	107	100	95
	30	310	220	175	135	120	110	103
	90	500	320	233	170	150	135	129
	183	1,200	790	580	400	330	280	250
Green River near Black Diamond	7	200	147	110	76	60	49	44
	30	270	185	135	89	70	57	51
	90	500	305	208	130	101	82	72
	183	1,400	820	550	335	255	200	175
Newaukum Creek near Black Diamond	7	24	19.3	16.3	13	11.3	10	9.2
	30	27	21.5	18.2	14.5	12.7	11.1	10.5
	90	32	25.5	21	16.1	14	12	11
	183	52	38	29.6	22	18.7	16.2	15
Big Soos Creek near Auburn	7	39	34	30	25	22	20	18.7
	30	44	37	32	26.5	23.5	21	20
	90	51	42	36	29	25.5	22.5	21
	183	80	59	47	37	32.5	29	27.5
Green River near Auburn	7	290	220	176	130	107	90	82
	30	360	270	208	147	118	96	86
	90	550	400	295	198	156	125	110
	183	1,450	950	670	430	335	270	240
Green River at Tukwila	7	335	270	220	168	140	120	110
	30	405	315	250	185	155	130	120
	90	640	445	335	235	195	166	150
	183	1,600	1,080	770	490	380	295	260

Dispersion and Time of Travel

Because the Green-Duwamish River carries large quantities of waste, studies have been needed to provide quantitative data on travel time and longitudinal dispersion of pollutants. These data have been obtained by introducing a tracer material into the river and measuring the concentration and time of travel of the tracer at various downstream points. From these measurements, dispersion coefficients are computed (Fischer, in press).

Using the fluorescent dye, rhodamine B, dispersion and time-of-travel studies for the Green-Duwamish River were made in the reach between Palmer and Tukwila in April 1965 by the Geological Survey. The tidal reach downstream from Tukwila was studied in October 1964 (Fischer, in press) and August 1965 (William's, in press). Profiles of discharge and of the travel time of maximum dye concentrations with respect to river miles are illustrated in Figure 84. Discharge of the Green River during this study ranged from about 3,500 cfs at Palmer to about 4,500 cfs at Tukwila. Most of the increase in discharge was in the Palmer-Auburn reach, and about half that increase is attributed to inflow from Newaukum and Big Soos Creeks.

The measured time of travel of the peak concentrations increased with distance downstream. Near Palmer the time of travel was about 19 minutes per mile, and from Kent to Tukwila it was about 28 minutes per mile. The average time of travel from Palmer to Tukwila was 23 minutes per mile.

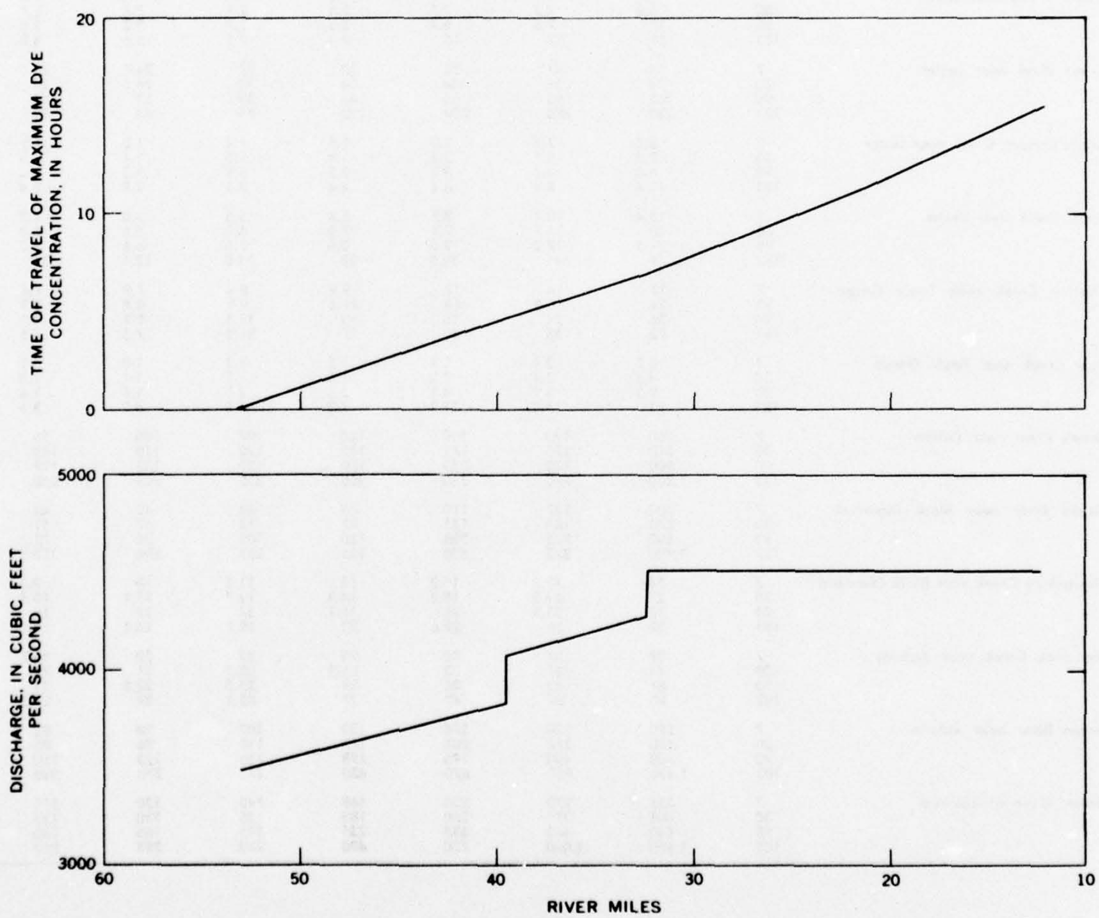


FIGURE 84.—Water discharge and time of travel of dye, Green River, April 20, 1965.

Dispersion coefficients ranged from 125 square feet per second in the Palmer-Auburn reach to 300 square feet per second in the Auburn-Tukwila reach. The coefficients reflect the increase in dispersion that occurs when a river passes from steep gradient and narrow channel to a low gradient and broad meandering channel.

STORAGE AND REGULATION

Natural Surface Storage

No glaciers are in the basins, and a study of the total amount of storage in natural lakes has not been made. Lake-surface areas, however, provide at least a comparative indication of the amount of water that is stored. The total lake surface in the study area is about 52.7 square miles, of which about 7.7 square miles consists of reservoirs.

Reservoirs

The following discussions and tabulations of principal existing reservoirs and potential storage sites in the Cedar-Green Basin apply to those that have a capacity of at least 5,000 acre-feet. Locations of existing reservoirs and potential storage sites in the basins are shown on a map (Figure 85).

Existing Reservoirs—Some regulation of the Cedar River is effected by Seattle's storage reservoirs, Masonry Pool and Chester Morse Lake. In 1900, the storage in Chester Morse Lake was increased by the construction of a crib dam. Later, in 1918, a masonry dam was completed about 2 miles downstream from the crib dam. The masonry dam impoundment was intended to inundate the crib dam and thereby provide increased storage for power generation and municipal supply. Shortly after construction of the masonry dam an immense washout occurred in the moraine that forms the right abutment of the dam. Since this failure, the level of Masonry Pool has been maintained at an altitude of about 1,547 feet, which is the crest altitude of the existing crib dam. At higher levels, seepage from the reservoir is excessive, and creates conditions that could result in another failure. The crib dam is capable of storing approximately 56,000 acre-feet in Chester Morse Lake (including active storage of 23,000 acre-feet) at the crest elevation. The capacity of Masonry Pool is approximately 4,000 acre-feet at the same altitude. At present (1967), the flow regimen of the Cedar River is not greatly affected by the existing storage.

The city of Seattle diverts municipal water from the Cedar River near Landsburg into off-stream storage in Lake Youngs. The capacity of Lake Youngs is approximately 11,000 acre-feet.

Howard A. Hanson Dam on the upper Green River provides 105,650 acre-feet of active storage. Major overbank flooding in the lower valley has been eliminated by the dam but some flooding occurs at the mouths of tributaries during periods of high discharge. Maximum storage is not retained in Howard A. Hanson Reservoir, but is dissipated as soon as possible after a flood to provide for the possibility of a second flood. During low-flow periods, the discharge below the dam is augmented so that approximately 100 cfs remains in the lower reaches for fishery enhancement.

Detailed information on existing reservoirs in the basin is presented in Table 36.

TABLE 36.—Existing reservoirs in the Cedar-Green Basins

Use: F, flood control; I, irrigation; N, navigation; P, Hydro-electric development; R, recreation; WS, Municipal and industrial water supply.

Name	*Location* Stream, T-R-S	Drainage area (sq mi)	Storage (acre-ft) Active	Storage (acre-ft) Inactive and/or dead	Storage (acre-ft) Total	Dam dimensions Ht (ft)	Dam dimensions Width (ft)	Reservoir area (acres)	Use	Applicant or owner	Remarks
Chester Morse Lk	Cedar R. 22-8-12	78	[1]23,000	[1]33,000	[1]56,000	15	--	1,682	P, WS	City of Seattle	Storage controlled by existing crib dam.
Masonry Pool Res.	Cedar R. 22-8-11	--	[1]4,000	0	[1],4000	120	--	280	P, WS	City of Seattle	Storage to elev. of crest of crib dam.
Youngs Lake	(From Cedar River) 22-5-11	--	--	--	11,000	25	--	700	WS	City of Seattle	Offstream storage.
Howard A. Hanson Dam	Green R. 21-8-28	220	106,000	0	106,000	235	450	2,240	F, WS	Corps of Engrs.	Flood control and storage to augment summer flows.

[1] Storage at elev. 1546.56 which is elevation of spillway of crib dam. Above this elevation the storage is combined behind the Masonry Dam and crib dam is flooded. Combined storage to elevation 1560.56 (spillway of Masonry Dam) is 85,000 acre-feet total and 52,000 acre-feet active. This storage is ineffective because of high rate of seepage from the Masonry Pool.

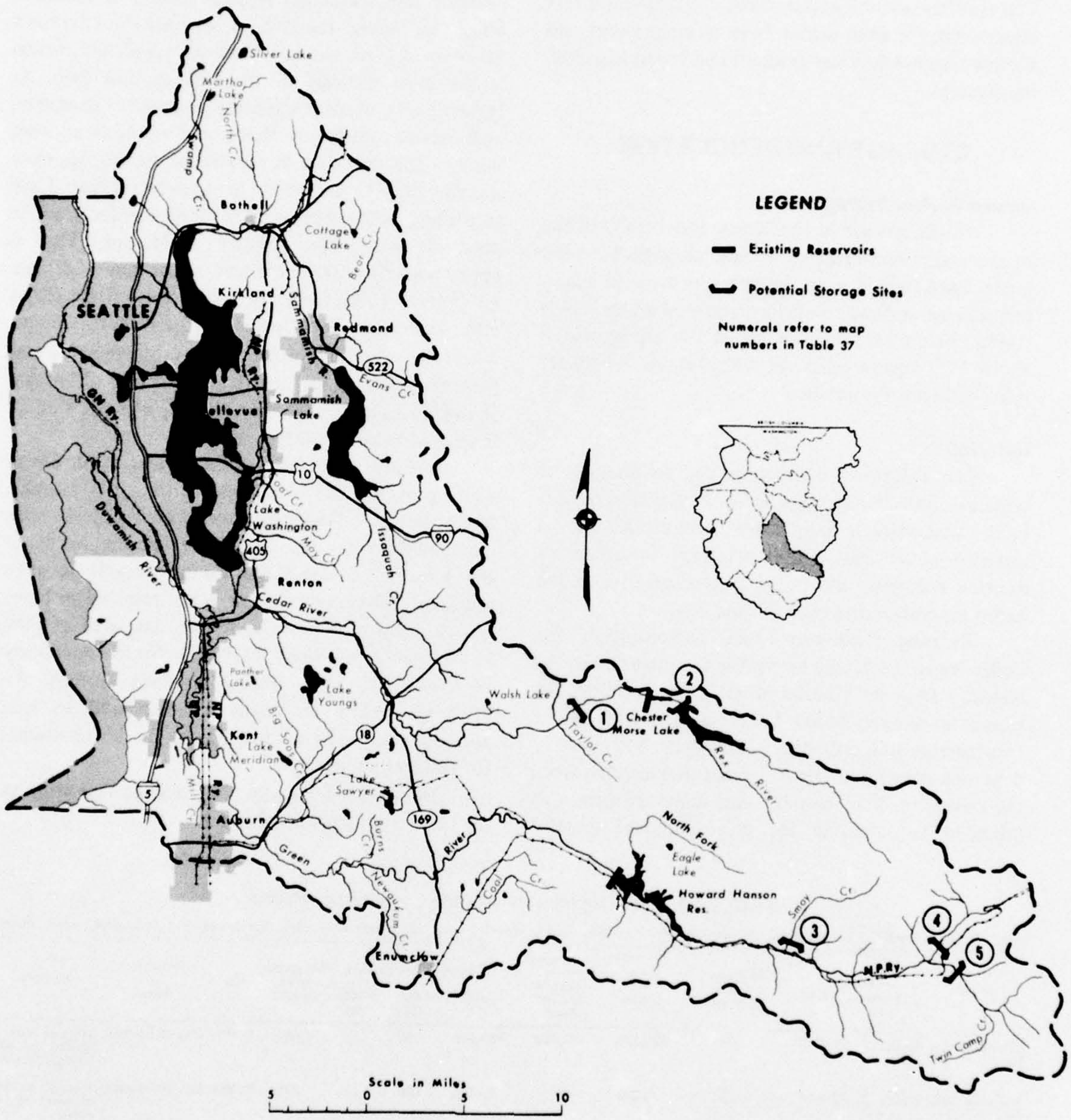


Figure 85. Existing Reservoirs and Potential Storage Sites in the Cedar—Green Basins

TABLE 37.—Potential storage sites in the Cedar-Green Basins

Map no.	Project name	T-R-S	River and mile	Total storage (1,000 acre-ft)	Drainage area (sq mi)	Remarks
1	Selleck	22-8-18	Cedar R. 27.2	--	84	
2	Chester Morse Lake	22-8-12	Cedar R.	61	78	Storage in existing lake by construction of new dam upstream from crib dam.
3	Weston (site 3)	20-11-28	Green R.	64	30	
4	Sunday Cr.	20-11-8	Sunday Cr. 1.3	--	23	
5	Smay Cr.	20-9-12	Smay Cr. 1.2	51.5	21	

Potential Storage Sites—Detailed information on potential storage sites in the basins is presented in Table 37.

DIVERSIONS

The City of Seattle diverts water from the Cedar River above Lansburg as its primary source of municipal supply. Between 200 and 300 cfs is diverted but the city's facilities are capable of diverting about 317 cfs.

The City of Seattle also diverts water from Chester Morse Lake and Masonry Pool to operate its Cedar Falls hydroelectric plant about 3 miles downstream. A maximum of 700 cfs can be diverted for operating the Cedar Falls plant. The water is discharged to Cedar River at Cedar Falls where the powerplant is located.

Since 1912 Green River has served as the main source of municipal and industrial water for the City of Tacoma. The facility has a capacity of 113 cfs which is diverted about 2½ miles southeast of Palmer.

The Washington Department of Fisheries Green River Salmon Hatchery on Soos Creek diverts 30 cfs from Soos Creek which is returned to the creek immediately below the hatchery ponds. Also, the Issaquah Salmon Hatchery, located at the town of Issaquah, diverts 10 cfs from Issaquah Creek and returns it to the creek below the pond.

An estimated 1,000 acre-feet of water is diverted from the streams in this basin for irrigation.

QUALITY OF SURFACE WATER

Chemical and Sanitary Quality

Chemical quality of surface water in the Cedar-Green Basins is excellent, and the water is acceptable for practically all uses with very little treatment. Water in the streams in this area is generally of a calcium-bicarbonate type that is low in dissolved-solids content and hardness. Data obtained from monthly sampling of the Green River near Auburn and the Cedar River at Renton indicate that the waters of both streams are soft and usually contain less than 60 ppm of dissolved solids. Headwaters of these streams serve as generally excellent sources of public supply for the cities of Seattle and Tacoma. During the winter and early spring, however, turbidity occasionally poses a problem in the use of these waters for public-supply purposes. The problem is not serious, though, because the turbidity remains above acceptable levels only during short periods of high storm runoff.

The water of the Sammamish River is slightly more mineralized than that of the Cedar and Green Rivers. Monthly sampling of the Sammamish River at Bothell showed a range in dissolved-solids content of 59 to 100 ppm. The slightly higher concentrations may be due to a larger percentage of ground water compared to increments in the Cedar and Green Rivers.

Sanitary quality of the lower reaches of major streams in the basins has been a problem for many years as a result of increasing population and accompanying waste disposal to the surface-water system. Brown and Caldwell (1958, p.1.) stated that in 1958, raw sewage from about 53% of the total population of metropolitan Seattle was being discharged through about 60 outfalls along the shorelines of the Duwamish River and Puget Sound and that Lake Washington was receiving treated sewage from an estimated 80,000 persons and indirect discharge from at least 4,000 private septic tanks. According to Peterson (1955) Lake Washington was in 1955 in the early stages of nutrient enrighment as a result of increasing inflow of raw and treated sewage. The enrichment in turn promoted the growth of algae. Monthly samples of the Duwamish River at Tukwila from October 1962 to April 1966 showed MPN values ranging between 230 and 240,000. One year of monthly

sampling beginning in October 1964 at the Chittenden Locks, the outlet of Lake Washington, showed MPN values ranging from 36 to 4,600.

A program was started by the Municipality of Metropolitan Seattle (METRO) in 1961 to establish a sewage system that would greatly reduce the contamination of surface waters in the Seattle area. In 1965, the $121 million construction program was two-thirds completed, and the deterioration of Lake Washington reportedly had been stemmed (Municipality of Metropolitan Seattle, 1965). Completion of the METRO program should see the elimination of most raw waste discharges into the Duwamish River, with an accompanying improvement in the sanitary quality of this stream.

Stream Temperatures

Temperature records are listed in Table 59 for three streams in the Cedar-Green Basins. Of these, two were measured at two different places; the Cedar River at Landsburg and Renton, and the Green River near Palmer and Auburn. Thermographs have been in operation at two of the five stations.

Minimum temperatures attained by the flow of Sammamish River at Bothell during the colder part of the year average about 40°F, and are the highest minimums in the basin. This may be a result of the stabilizing effect of Lake Sammamish, the source of the Sammamish River. The Green River at Palmer is the coldest major stream in this area, but it is not as cold as the streams of glacial origin. The Cedar River at Landsburg is slightly warmer than the Green. This difference may result from the influence of seepage from Chester Morse Lake and Masonry Pool.

Green River is warmed appreciably in the reach from Palmer to Auburn. Within this reach, especially in the Green River gorge, the stream receives a fairly large contribution of ground water. Additional ground water is added by Big Soos Creek, a stream that is fed largely be springs. Doubtless, the contribution of ground water has a stabilizing effect in all but the coldest and warmest months. Because of the reduction in discharge between Palmer and Auburn, extremes in temperature can exert a more significant heating or cooling effect. The July high of 75°F at Auburn, 10°F higher than at Palmer, and the December low of 33°F, 2° lower, demonstrate the magnitude of this effect. The average summer temperature of the Green at Auburn is among the highest of streams studied in the Puget Sound Area.

Sediment Transport

Sediment transport is discussed separately for the upper and lower drainages of the basins. The upper drainage consists of watersheds above Selleck on the Cedar River and above Palmer on the Green River, and the lower drainage includes the remaining areas downstream.

The upper drainage of the Cedar River basin is largely in mountainous terrain, where the soils are shallow and vary considerably in origin and texture. Above altitudes of about 3,000 feet, the shallow stony soil cover is derived from underlying bedrock. At lower altitudes, the soils are derived principally from glacial drift. A dense cover of vegetation on the steep slopes in the upper drainage of the Cedar River largely precludes excessive soil erosion; removal of vegetation results in sheet and rill erosion of the fine sediments during periods of intense rain. Some of the eroded sediments are deposited in lakes and swamps and, therefore, do not reach the streams. Stream-channel conditions in the upper drainage favor occasional sloughing of the bank materials, particularly during periods of high runoff. Generally, streams in the Cedar-Green Basins transport only small amounts of sediments and have suspended-sediment concentrations less than 20 ppm.

In the mountainous upper-drainage terrain of the Green River, soils on the steep slopes are shallow and vary considerably in origin and in texture; gravel, cobbles, and boulders are prominent. Excessive erosion of soils in the upper drainage of the Green River is largely precluded by a cover of vegetation. Because the upper drainage is a limited access watershed, activities of man that would contribute to erosion are limited. Bars of gravel in the Green River indicate that there is considerable movement of bed materials during periods of high runoff.

Sediment data collected daily on the Green River near Palmer during the period 1951-57 showed yearly loads that varied from 6,370 tons in 1952 to 125,500 tons in 1956 and averaged 59,800 tons. Suspended-sediment concentrations during the period of collection ranged from 1 to 3,140 ppm.

A representative analysis showed that the sediments consisted of 23% clay, 48% silt, and 29% sand. The tributaries of the Green River in the upper drainage generally have suspended-sediment concentrations of less than 10 ppm except during periods of high runoff.

The lower drainage of the Cedar River is formed on terrain that is typical of lowlands in the

Puget Sound Area. Soils on flood plains are derived from alluvium, and are permeable, while soils on the uplands are derived from glacial outwash and are moderately well drained. Swampy or marshy areas containing peat or muck are numerous along the lower reaches of the Sammamish River and Issaquah Creek. These areas receive much of the sediment eroded from adjacent uplands. Vegetal cover prevents excessive erosion on steeper slopes except in areas of urban development and road construction. Bank sloughing and movement of bed materials have occurred along lower reaches of the Cedar River but have been reduced by channel improvement and streamflow regulation. Suspended-sediment data collected from the Cedar River during the period 1962-65 indicate that the river transports about 60,000 tons of sediment annually on the average. A representative analysis shows 17% clay, 50% silt, and 33% sand.

The lower drainage areas of the Green River contain soils that vary from well drained to poorly drained. The well to moderately drained soils are derived from till and outwash, whereas the poorly drained soils are derived largely from lake deposits, alluvium, and organic materials. Excessive erosion of soils on the steeper slopes is largely precluded by a profuse vegetation. Numerous lakes and marshy areas in the lower reaches of the Green River contribute little sediment to the river and provide catchment areas for sediment eroded from higher areas. In its lower reaches, the Green River channel cuts through glacial and alluvial deposits, which are eroded during periods of high runoff.

Suspended-sediment data have been collected from the Green River at Tukwila during the period 1964-66. The sediment load was 125,000 tons in 1964 and 375,000 tons in 1965. The maximum concentration was 1,590 ppm and the maximum daily load was 31,000 tons. The representative composition is 18% clay, 35% silt, and 47% sand. The bedload of the Green River at the Tukwila site comprises about 10 to 40% of the total sediment load. The recent development of an industrial area near Tukwila apparently has caused significantly increased sediment contribution to the Green River. Tributaries of the Green River generally have suspended-sediment concentration of less than 10 ppm.

GROUND WATER

Ground Water supplies are plentiful in many places in the Cedar-Green Basins. Ground-water resources are discussed separately, by lowland and mountain areas: the lowlands are generally west of a line through Hobart and Enumclaw, and the mountains are to the east.

LOWLANDS

Geology and Ground Water Occurrence

Most of the important aquifers in the lowlands are contained in coarse Quaternary deposits which are rather continuous over about 670 square miles. Older consolidated rocks crop out in an area east of Renton. Locally near Puget Sound the thickness of Quaternary sediments may exceed 2,000 feet. In most inland areas, aquifers capable of continuously furnishing large quantities of fresh water to wells usually exist as deep as 400 feet below sea level, but toward Puget Sound the base of fresh water becomes shallower. Water levels are generally within 100 feet of land surface.

Quaternary sediments exposed at the surface are mainly till, recessional outwash, alluvium, and mudflow deposits. The uplands are covered principally by till. The till is as much as 150 feet thick on the higher upland to the north; it is breached and truncated along some plateau margins, and it thins to a featheredge over consolidated rocks in the area east of Renton. Because the till is composed largely of compacted fine materials, it is not an important aquifer, even though it is somewhat permeable.

Locally, till is mantled with recessional outwash, which is composed mostly of gravel and sand. On the uplands, the outwash occurs as thin isolated deposits, and is not a dependable aquifer. Along principal streams in the north and along the northern part of Lake Washington, the outwash deposits are more extensive and of greater thickness, locally exceeding 100 feet. To the southeast, large areas are blanketed with recessional outwash that is locally as much as 50 feet thick, saturated thicknesses are most commonly 20 feet or less, however. Water-yielding properties of the recessional outwash aquifers seem most favorable in areas north of Lake Sawyer and along the Green River east of Auburn. Recessional

outwash is overlain by alluvium in many places, particularly on the Sammamish flood plain.

Alluvium occurs mainly on flood plain of the Sammamish, Cedar and Green Rivers. It is composed principally of sand and gravel, except in the Green River valley north of Auburn, where fine sand, silt, and clay predominate. The deposits are notably coarse in the Renton area. In the Green River valley north of Auburn, the alluvium seems to be thickest, which locally is 300 feet or more. Alluvium is saturated to about river level; deeper alluvial aquifers in the lower Green River valley are confined under artesian pressure.

On the upland east of Auburn and south of the Green River, mudflow deposits overlie both till and recessional outwash at the land surface. The mudflows are apparently less permeable than till, and serve as confining layers for underlying artesian aquifers, principally in recessional outwash. Thickness of the mudflows varies considerably, but is not known to exceed 75 feet.

Quaternary sedimentary deposits older than till are exposed mostly along the margins of some of the uplands, particularly along Puget Sound and the lower Green River valley. These older sediments include sand and gravel aquifers that contain fresh water at most places in the basin. The thickness of the pre-till aquifers varies considerably, but generally totals less than 150 feet. Water in these aquifers characteristically is confined under artesian pressure except beneath upland areas, where water-table conditions exist generally.

Consolidated rocks of pre-Quaternary age usually do not contain significant aquifers; however, moderate well yields are obtainable from conglomerate and sandstone of Tertiary age in the interlake area near Eastgate.

Practically all recharge to the lowland aquifers is by infiltration of precipitation. The aquifers are estimated conservatively to receive about 120,000 acre-feet of recharge in an average year, but not all of the recharge can be intercepted by wells. Opportunities for recharge may exist along Lake Washington and Lake Sammamish, along Big Soos Creek, and on flood plains of Bear Creek, the Sammamish River, the lower Green River near Renton, and lower Issaquah Creek.

The natural discharge of ground water is mostly into the lower drainages of the Green, Cedar, and Sammamish Rivers and the two large lakes east of Seattle. Considerable quantities of ground water are probably discharged into Puget Sound through springs that occur both above and below tidewater level.

Quality of Ground Water

Water in most aquifers is generally low in dissolved solids and acceptable for practically all uses. Dissolved-solids concentration is characteristically less than 200 ppm in the shallower aquifers, and somewhat greater—up to 500 ppm—in deeper aquifers. Highly mineralized water occurs in some aquifers adjacent to Puget Sound. Brackish water occurs in the deeper aquifers locally, and deep aquifers in the southern part of the basins commonly yield water containing more than 50 ppm of sodium. Shallow aquifers near Puget Sound usually contain traces of sea water, but only incipient encroachment has been detected. Hardness of the ground water is generally less than 120 ppm. In waters containing less than 200 ppm of dissolved solids, silica content ranges from 9 to 65 ppm, averaging about 30 ppm. Well owners commonly report objectionable concentrations of iron, particularly in water from shallow wells.

Utilization and Development

Ground water in the lowlands is used mostly for public supply and irrigation, although substantial amounts are pumped from many small-capacity wells for individual household and livestock uses. Ground water is used by Kent, Renton, and Auburn; part of each city's supply is obtained from springs and part from wells. The wells used by many communities near Seattle produce water from Quaternary subtill aquifers and a few from pre-Quaternary consolidated rocks. The Renton wells tap aquifers in an alluvial fan of the Cedar River. Irrigation with ground-water occurs mostly in the lower Green River valley, and on the plateau east of Auburn and south of the Green River.

Most large-capacity wells in the lowlands are completed in aquifers below till and mudflow deposits. Most of these wells yield less than 1,000 gpm. The largest-yielding wells produce from alluvial aquifers; Renton city wells located near the mouth of the Cedar River pump as much as 3,000 gpm. These and other wells used for municipal and industrial supply are generally more thoroughly completed and developed than wells that are used for other purposes. Figure 23 shows order-of-magnitude estimates of expected well yields in the basins. Subtill aquifers beneath the valley of Issaquah Creek near Issaquah

may also support large sustained well yields. High yields may not be possible on the plateau in Snohomish County owing to low permeability of the subtill aquifers. In the general area between Issaquah and Renton, water wells pump as much as 450 gpm from aquifers in consolidated rocks, but inadequacy of recharge to these aquifers may preclude sustained major development. Wells that tap deep aquifers below the flood plains and low-lying areas marginal to plateaus may flow.

MOUNTAINS

In the mountains, sand and gravel aquifers occur in some of the Quaternary deposits, which occupy about 100 square miles. Till is exposed at the surface principally in the area north of the Cedar River in T. 7N., R. 22 E.

Most of the deposits are alluvium and outwash. Alluvium occurs mainly on a narrow flood plain several miles upstream from Palmer. Geologic information suggests that the alluvial deposits are not thick; nonetheless they contain coarse gravels that can be easily recharged by infiltration of precipitation and by induced flow from the Green River. Similarly, outwash deposits are not thick, but are conducive to recharge.

Most ground-water discharge in the mountain areas is into the streams that dissect the aquifers, but significant amounts of ground water in the vicinity of Cedar Falls are lost by underflow through outwash into the Snoqualmie basin, principally because of seepage from reservoirs.

Water wells in the mountains, which are used mostly for individual household purposes, are completed in aquifers in outwash. The wells are generally less than 100 feet deep, many yield at least 20 gpm, and depths to water are mostly less than 30 feet. Except for high iron content, which reportedly is objectionable to many users, the mineral content of the water is low. In areas where Quaternary materials are absent, ground water is obtainable only from consolidated rocks, which yield 10 gpm or less to wells.

PUYALLUP BASIN

SURFACE WATER

The Puyallup Basin comprises 1,254 square miles, including 1,203 square miles of land and inland water. A map of the basin is shown in Figure 93. The largest and most important stream in the basin, the Puyallup River, drains 972 square miles, the upper part of which is rugged and mountainous and the lower part flat or rolling. The Puyallup River proper begins at the Puyallup and Tacoma glaciers on Mount Rainier, and flows northwestward about 46 miles to Commencement Bay at Tacoma, with a fall of more than 3,000 feet. For the first 20 miles the flow is very rapid as it passes through a rugged country with no lowlands; the lower 8 miles of this section is a deep canyon. At the foot of the canyon the river flows out onto the flat valley, and has a comparatively flat gradient from there to its mouth.

The principal tributary of the Puyallup is the White River, which rises at Mount Rainier's Emmons Glacier and enters the Puyallup at mile 10.5. From its sources at the northeastern glaciers of Mount Rainier and on the western slope of the Cascade Range to its emergence from the foothills onto the lowlands, the river flows for 57 miles in a northwesterly direction through a rather wide valley with a high, but comparatively uniform. gradient. Before 1906. the White River discharged partly into the Duwamish River to the north and partly into the Puyallup to the south. Since then, the entire flow has been diverted into the Puyallup. Greenwater River, the main tributary of the White drains an area of 76 square miles.

The Carbon River, about 30 miles in length and the second largest tributary to the Puyallup, joins the river about 2½ miles below the town of Orting. The Carbon River has its source at Carbon Glacier on the north slope of Mount Rainier at an altitude of about 3,600 feet. The Mowich River, the third largest tributary, originates at the North and South Mowich Glaciers on the west side of Mount Rainier at altitudes of about 5,500 and 4,800 feet, respectively. Flowing in a westerly direction, the Mowich enters the Puyallup River from the east about 22 miles above the mouth of the Carbon River, or 41 miles above the mouth of Puyallup. Stream slopes range from 75 feet per mile in the upper reaches to about 30 feet per mile in the lower valley, with generally steeper slopes on the principal tributaries.

STREAMFLOW

Runoff Characteristics

The Puyallup River and most of its tributaries, including the White and Carbon Rivers, drain approximately 60% of the slopes of Mt. Rainier. Direct runoff measurements from these high alpine areas are not available; however, other data indicate that the average annual contribution exceeds 120 inches. Runoff production near the mouth of this stream system is estimated to be about 20 inches annually. The mean runoff from the entire 1,203 square miles of this basin is estimated to be 41 inches, or 2.7 million acre-feet.

On the main stem of the Puyallup River, records obtained at a gage near Electron indicate that the mean annual discharge from the western foothills and slopes of Mount Rainier is about 539 cfs, or about 390,000 acre-feet per year. Although this area has excellent exposure to prevailing storms, unit-runoff production is considerably less than that of the southern Olympic slopes in the West Sound Basin. Approximately 5.8 cfs per square mile is produced on these slopes of Mount Rainier compared to about 9.3 cfs per square mile from the South Fork of the Skokomish River drainage in the Olympic Mountains.

Unit runoff decreases rapidly below the Electron gage, and in the drainage area between this gage and the station near Orting, the mean annual unit discharge is only 2.1 cfs per square mile. In total, the mean annual runoff of the Puyallup River above the gage near Orting for the period, 1931-60, is 703 cfs, or 509,000 acre-feet per year; this is equivalent to 4.1 cfs per square mile.

Runoff from the upper reaches of the Carbon River drainage is comparable to that of the Puyallup River above Electron. At the gaging station near Fairfax, mean annual discharge from the Carbon River was 426 cfs, or 309,000 acre-feet during the period 1931-60. In terms of unit runoff, this is equal to 5.4 cfs per square mile.

Runoff from nearly one-half of this basin is measured at a gaging station on the White River near Buckley. During the reference 30-year period, mean annual discharge averaged 1,490 cfs or 1,080,000 acre-feet. Because production from both low and high altitude areas is sampled at this station, the runoff per square mile amounts to only 3.7 cfs.

Contributions from virtually the entire basin are measured at the gaging station on the Puyallup River at Puyallup. An excellent long-term record is available for this site, and it shows that the mean annual discharge during 1931-60 averaged 3,440 cfs which is equivalent to a mean annual yield of 2,490,000 acre-feet. The average unit discharge and yield for the basin is 3.6 cfs per square mile.

Long-term annual runoff trends in this basin are presented in Figure 86. This chart shows that several consecutive years of below average or above average runoff occurred occasionally, but that in general, no definite pattern of cyclic fluctuation is apparent and the variations appear to be basically random. During the period of streamflow record for the Puyallup River, the maximum yearly mean discharge of 5,180 cfs occurred in the 1960 water year, and minimum yearly mean discharge of 2,090 cfs occurred during the 1941 water year. These flows represent 151% and 61%, respectively, of the mean discharge of 1931-60.

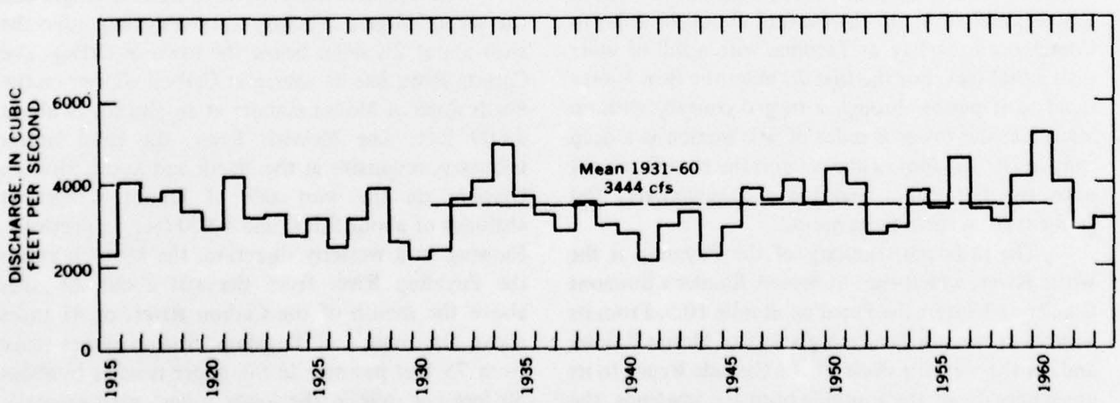


FIGURE 86.—Annual discharges, Puyallup River at Puyallup.

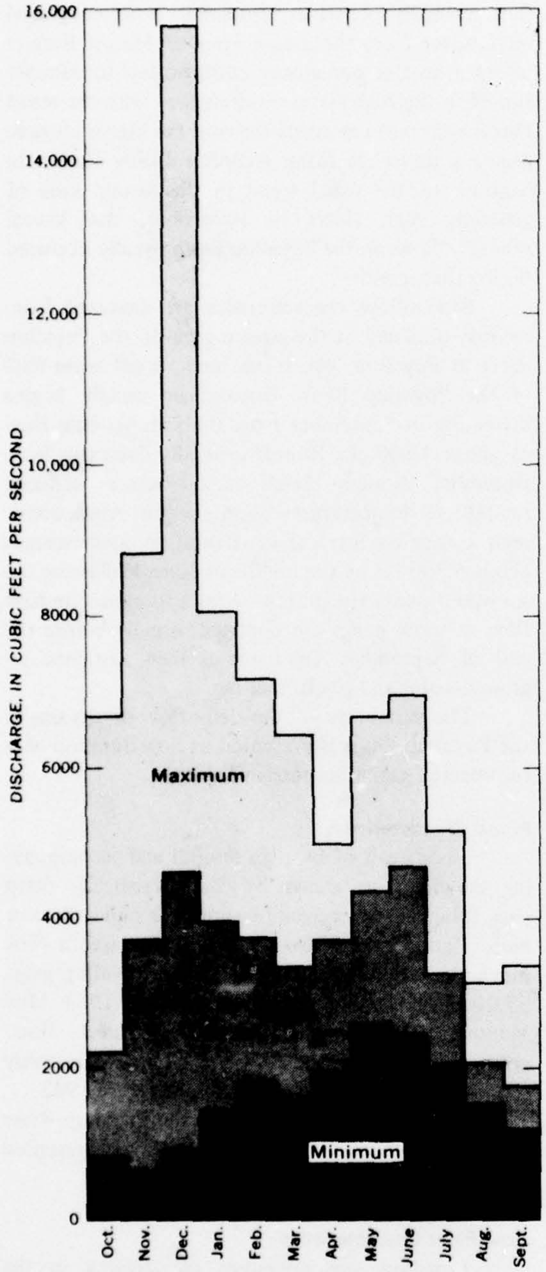


FIGURE 87.–Maximum, mean and minimum monthly discharges, Puyallup River at Puyallup, 1931-60.

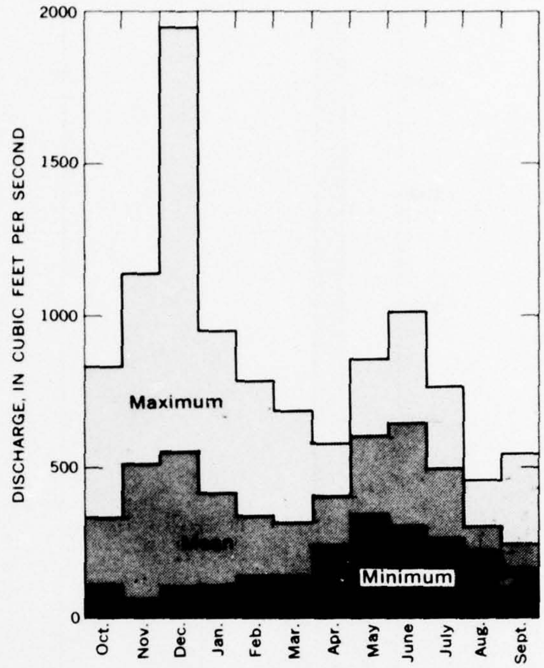


FIGURE 88.–Maximum, mean and minimum monthly discharges, Carbon River near Fairfax, 1931-60.

Bar charts of mean monthly flow at selected gaging stations in the Puyallup Basin (Figures 87-89) delineate two basic peak flow periods, one in winter and another in late spring. The period of lowest flows generally occurs during the late summer.

At the higher altitudes, monthly peaks are greater during the spring than winter. This results from the greater influence of snow accumulation and melt in these streams. Lower altitude streams exhibit nearly equal average monthly peaks during both periods. The range in peak flow variations is decidedly greater during the winter months, and is greatest in December.

The relatively high level of summer flows in this basin bears out the significance of glacial storage in maintaining streamflow during summer periods of deficient precipitation. The average low monthly

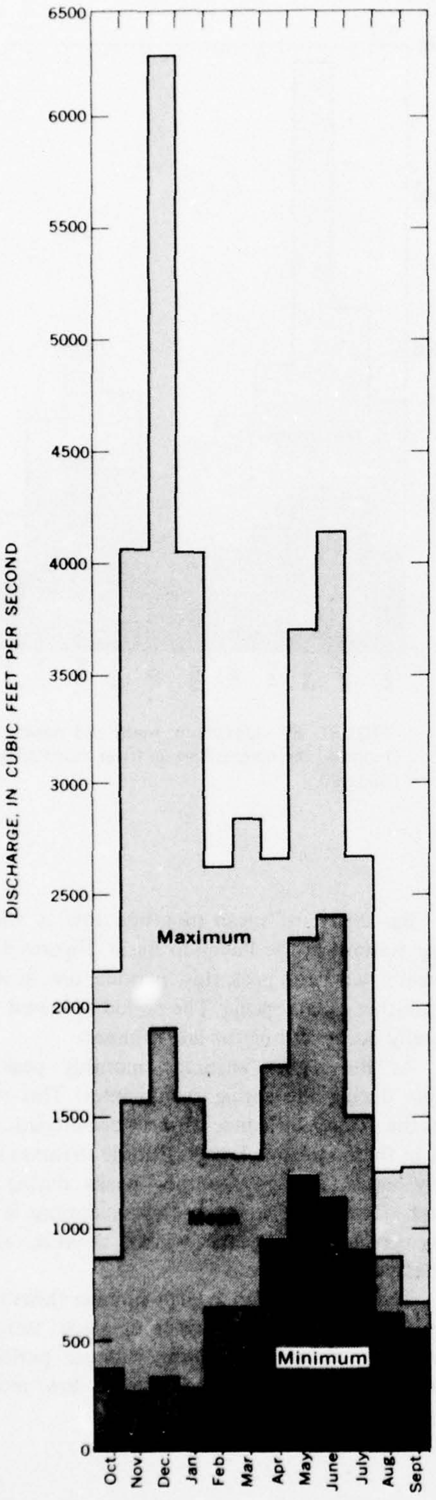


FIGURE 89.–Maximum, mean and minimum monthly discharges, White River near Buckley, 1931-60.

flow normally occurs in September; however, glacial melt water from the alpine areas of Mount Rainier offers a greater percentage contribution to summer runoff in the high elevation drainages, with the result that lowest mean monthly flows at the higher altitude gaging stations are often recorded during March. In contrast to the usual trend in the Study Area of generally high flows in November, the lowest monthly flows in the Puyallup Basin usually occurred during that month.

Streamflow characteristics are analyzed from records obtained at the stream gage on the Puyallup River at Puyallup, which measures runoff from 98% of the Puyallup Basin. Streamflow usually begins increasing in September from the summer base flow of about 1,600 cfs. Runoff generally decreases from December through March as a result of reduced rainfall. As temperatures begin rising in April, snowmelt causes an increase in streamflow and averages about 5,300 cfs by the middle of June. Following the snowmelt peak, streamflow recedes to minimum base flow as snow packs are depleted, usually before the end of September. Discharge is then sustained by ground-water and glacial melting.

The variability of the daily flow of streams in the Puyallup Basin is presented as flow duration data for selected gaging stations in Table 38.

Flood Characteristics

Floods caused by high rainfall and accompanying snowmelt are shown by characteristically sharp rises followed by recessions almost as rapid. Two or more flood peaks often occur within 2 weeks. The maximum discharge recorded at the Puyallup gage, 57,000 cfs, occurred on December 10, 1933. Mud Mountain Dam, a U.S. Corps of Engineers flood control project on the White River, has effectively reduced the magnitudes of large floods since 1942.

Flood frequency curves for the Puyallup River at Puyallup during the period 1915-64 are presented in Figure 90.

Low-Flow Characteristics

Low-flow characteristics of streams in the Puyallup Basin are compared using indexes from low-flow frequency curves at 12 gaging stations (Table 39). The low-flow indexes are excellent in the upper Puyallup, White, and Carbon River basin (Fig. 22). The indexes are fair for streams in the middle part of the basin and are poor for those that head in lowlands adjacent to Puget Sound. In general, the

TABLE 38.—Flow-duration data for selected gaging stations in the Puyallup Basin

Gaging station	Period of analysis	Flow, in cubic feet per second, which was equaled or exceeded for indicated percent of time											
		99	95	90	80	70	50	30	20	10	5	1	0.1
Clover Creek near Tillicum	1950-54	0	0	0.45	4.1	8.8	23	50	80	134	174	270	430
Leach Creek near Fircrest	1958-64	1.55	1.75	1.9	2.2	2.55	3.2	3.8	4.5	6.4	10	18	35
Chambers Creek below Leach Creek near Steilacoom	1939-40, 1944-64	35	41	44	51	59	85	130	165	220	270	430	620
Puyallup River near Electron	1910-33, 1945-49, 1958-64	144	185	220	275	330	445	600	720	940	1,180	1,960	3,900
Kapowsin Creek near Kapowsin	1928-32, 1942-57	1.9	3.3	4.7	7.9	15	35	58	77	113	153	270	465
Puyallup River near Orting	1932-61	170	252	310	390	450	590	770	920	1,210	1,600	2,950	5,800
Carbon River near Fairfax	1930-58	77	120	148	190	235	330	475	580	760	950	1,660	3,600
South Prairie Creek at South Prairie	1950-64	32	41	50	78	117	190	280	340	475	650	1,250	2,600
White River at Greenwater	1930-64	195	280	336	420	500	690	980	1,200	1,590	1,960	3,000	5,300
Greenwater River at Greenwater	1930-64	30	36	43	59	80	144	245	330	455	580	940	1,700
White River near Buckley	1930-64	300	460	555	700	840	1,150	1,660	2,060	2,750	3,400	5,100	10,000

slope and spacing indexes, which show the variability of low flows, are less than the regional average except for Kapowsin Creek. Chambers Creek has the least variation and maintains a fairly constant flow.

Low-flow frequency data for the 12 sites are listed in Table 40. Frequency curves for 2 of the 12 sites are shown in Figures 91 and 92.

Low-flow indexes range from 0.12 cfs per square mile for White River near Sumner to 2.10 cfs per square mile for Puyallup River near Electron. Glacial melt water in the Puyallup, Carbon, and White Rivers account for the large low-flow indexes for these rivers. The values decrease along the Puyallup River from 2.10 near Electron to 1.24 at Puyallup. The extremely small index for White River near Sumner does not represent natural conditions because of diversion of a large part of the flow around the station. Greenwater River and South Prairie Creek drain about the same size areas as Carbon River, but because they do not have glacial sources, their low-flow indexes are much smaller; 0.56 and 0.52, respectively. Kapowsin Creek has an index of 0.15. (In the Nisqually-Deschutes Basins, Tanwax Creek, Ohop Creek, and Mashel River have similar values.) The index of only 0.39 cfs per square mile for Chambers Creek is much smaller than normally would be expected for this basin, because the area is underlain by recessional outwash and alluvium containing large volumes of ground water. However, much of the ground water discharges into American and Sequallitchew Lakes rather than into Chambers Creek.

Slope-indexes for streams in the basin range from 1.32 for Chambers Creek to 2.94 for Kapowsin Creek. The values for the other streams are between 1.35 and 1.61. The large value for Kapowsin Creek is possibly the result of seepage and evaporation losses in Kapowsin Lake. The high permeability and porosity of the alluvial and outwash sediments in the Chambers Creek basin account for the small slope index there and the sustained low flows from year to year. The fairly uniform slope-index values for the other stations are all less than the average in the Puget Sound Area.

Spacing indexes range from 1.52 in the Chambers Creek basin to 4.47 in the Kapowsin Creek basin. The permeability of the underlying rocks probably has the greatest influence on the spacing between the frequency curves. In the Chambers Creek basin unconsolidated sediments allow rainfall to infiltrate readily, and precipitation does not generally result in surface runoff, which accounts for the narrow spacing between frequency curves. In the Kapowsin Creek basin, wide spacing between frequency curves reflects surface conditions that favor rapid runoff and little infiltration. Glaciers also influence the spacing index as shown by the fairly low values in some basins. For glacier-fed streams the values range between 2.06 for White River basin above Greenwater to 2.80 for Carbon River basin. Nonglacial streams, Greenwater River and South Prairie Creek have curves with somewhat wider spacing as indicated by indexes of 2.92 and 3.37, respectively.

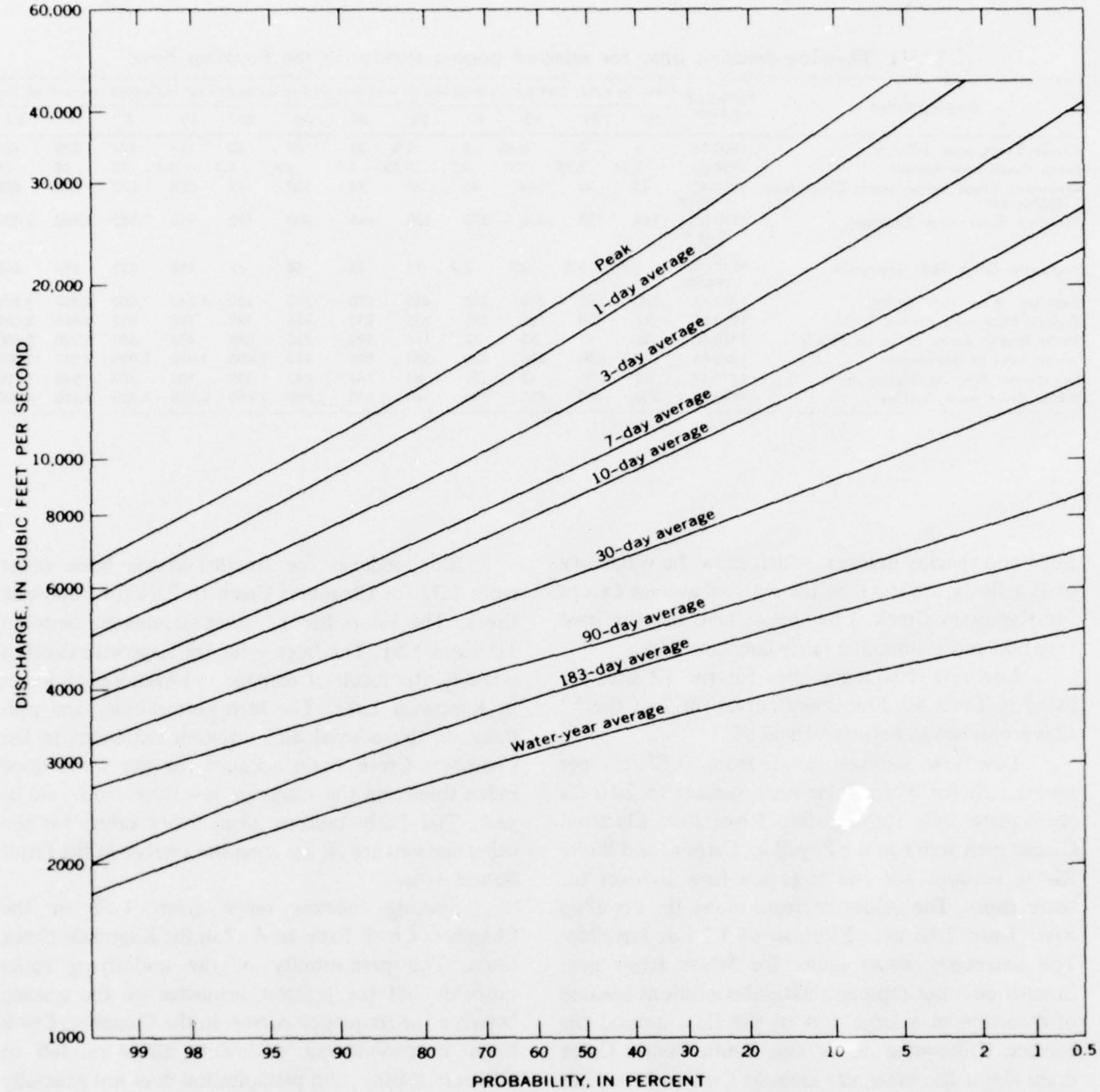


FIGURE 90.–Probability curves of annual maximum flows for specified time periods, Puyallup River at Puyallup.

TABLE 39.—Low-flow characteristics for selected gaging stations in the Puyallup Basin

Gaging station	Drainage area	Low-flow index	Slope index	Spacing index
Chambers Creek below Leach Creek near Steilacoom	104	.39	1.32	1.51
Puyallup River near Electron	92.8	2.10	1.48	2.56
Kapowsin Creek near Kapowsin	25.9	.15	2.92	4.47
Puyallup River near Orting	172	1.48	1.50	2.36
Carbon River near Fairfax	78.9	1.70	1.51	2.80
South Prairie Creek at South Prairie	79.5	.52	1.45	3.37
Puyallup River at Alderton	438	1.19	1.45	2.60
White River at Greenwater	216	1.53	1.37	2.06
Greenwater River at Greenwater	73.5	.56	1.37	2.93
White River near Buckley	401	1.20	1.60	2.38
White River near Sumner	470	.12	1.57	4.83
Puyallup River at Puyallup	948	1.24	1.44	2.29

TABLE 40.—Low-flow frequency data for selected gaging stations in the Puyallup Basin
[Discharge adjusted to base period April 1, 1946, to March 31, 1964]

Gaging station	Number of consecutive days	Streamflow in cfs, for indicated recurrence intervals, in years						
		1.05	1.30	2.0	5	10	20	30
Chambers Creek below Leach Creek near Steilacoom	7	66	50	41	34	32	31	30
	30	72	54	45	38	35	33	32
	90	79	59	49	41	38	36	35
	183	89	73	62	51	46	42	40
Puyallup River near Electron	7	270	225	195	158	146	132	125
	30	365	305	260	200	183	165	155
	90	500	440	390	315	290	265	250
	183	720	580	500	400	375	350	330
Kapowsin Creek near Kapowsin	7	9.2	5.6	3.8	2.3	1.7	1.3	1.1
	30	11	6.8	4.7	2.9	2.2	1.7	1.5
	90	20	10.3	6.6	3.9	3.0	2.4	2.1
	183	38	24	17	10.7	8.2	6.4	5.6
Puyallup River near Orting	7	380	305	255	210	188	170	162
	30	440	380	335	285	260	240	225
	90	580	510	460	410	380	360	350
	183	800	680	600	520	490	470	460
Carbon River near Fairfax	7	200	160	134	110	98	89	85
	30	265	207	170	133	118	105	99
	90	350	300	260	220	197	177	167
	183	550	445	375	300	265	240	225
South Prairie Creek at South Prairie	7	53	46	41	34	30	28	26
	30	68	56	48	39	35	31	30
	90	130	90	68	49	41	35	33
	183	235	180	138	96	77	62	56
Puyallup River at Alderton	7	730	600	520	440	400	360	335
	30	950	820	710	580	510	445	410
	90	1,300	1,120	980	820	740	650	610
	183	1,800	1,550	1,350	1,100	990	860	800
White River at Greenwater	7	410	360	330	280	260	240	225
	30	520	440	390	330	300	280	265
	90	730	580	500	440	410	390	380
	183	1,320	890	680	530	480	450	440
Greenwater River at Greenwater	7	67	51	41	34	32	30	29
	30	74	56	47	38	35	33	32
	90	110	77	60	47	42	39	37
	183	280	172	120	81	66	56	51
White River near Buckley	7	640	550	480	390	340	300	280
	30	810	690	600	500	440	400	375
	90	1,150	870	740	640	580	540	510
	183	2,000	1,450	1,140	910	820	770	740
White River near Sumner	7	86	70	58	47	41	37	34
	30	110	84	70	56	50	46	44
	90	165	127	102	76	64	55	50
	183	800	460	280	140	100	73	62
Puyallup River at Puyallup	7	1,460	1,300	1,180	1,010	910	820	770
	30	1,780	1,600	1,440	1,250	1,150	1,050	1,000
	90	2,650	2,200	1,900	1,590	1,440	1,300	1,230
	183	4,100	3,200	2,700	2,200	2,000	1,800	1,700

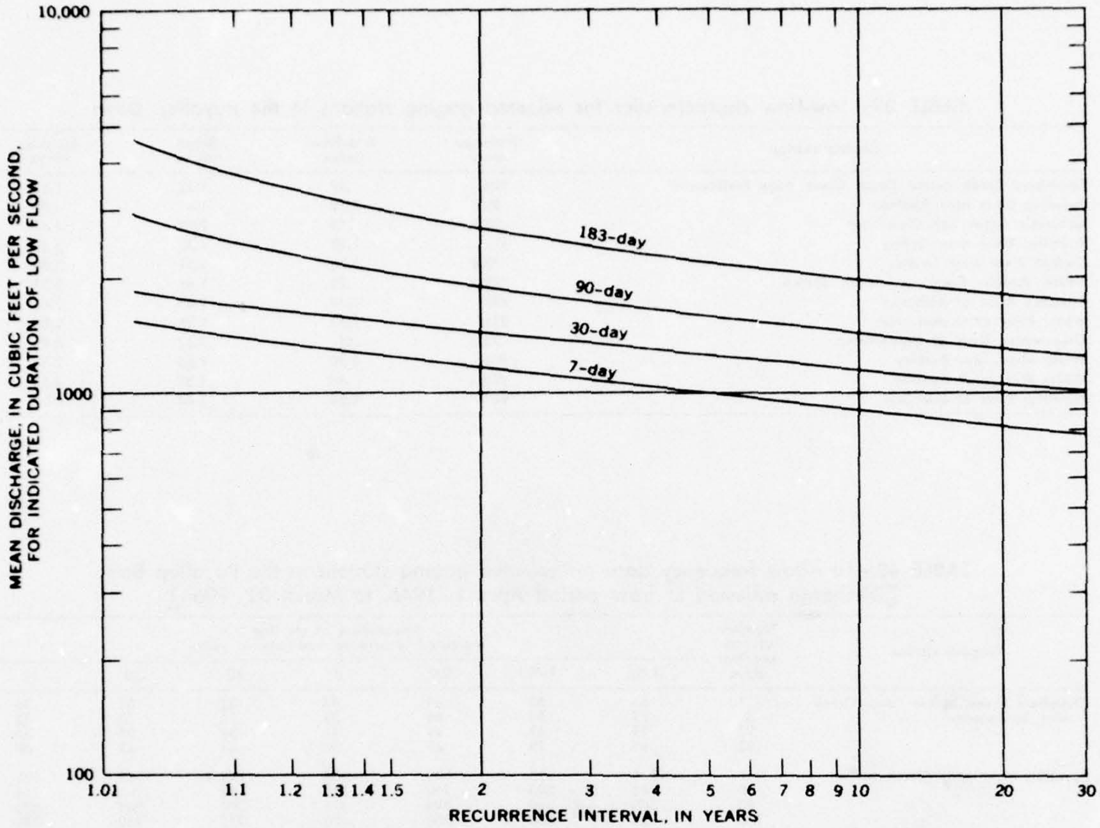


FIGURE 91.—Low-flow frequency, Puyallup River at Puyallup, 1946-63.

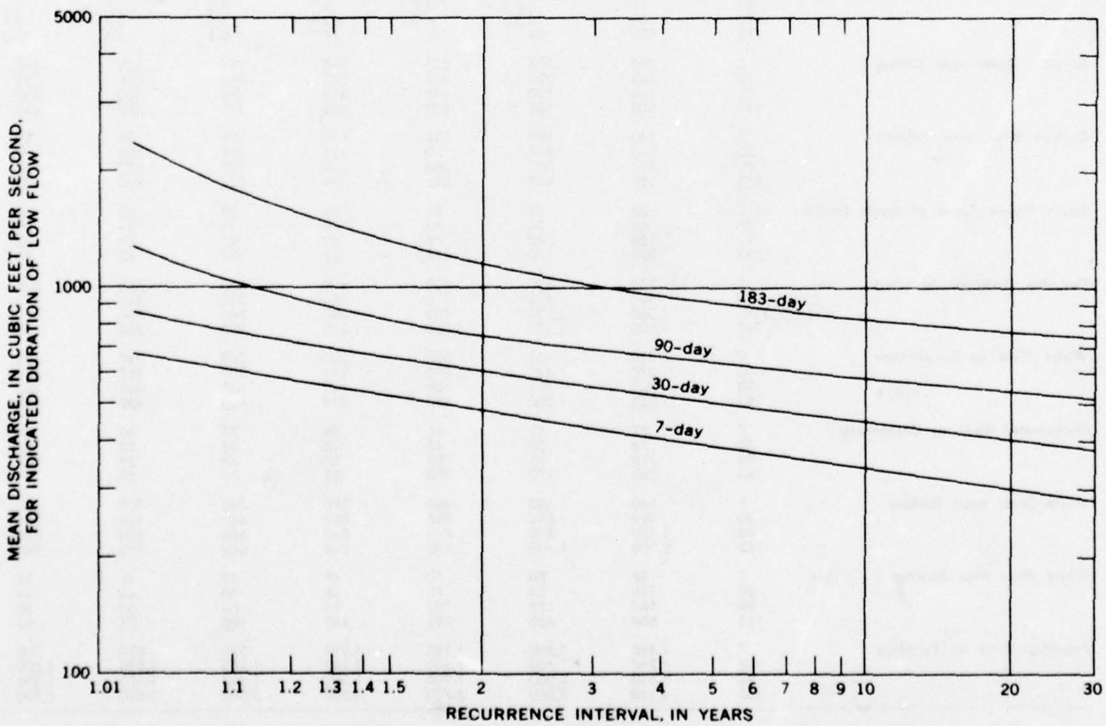


FIGURE 92.—Low-flow frequency, White River near Buckley, 1946-63.

TABLE 41.—Existing reservoirs in the Puyallup Basin

Use: F, flood control; P, Hydro-electric development

Name	Location Stream, T-R-S	Drainage area (sq mi)	Storage (Acre-ft) Active	Storage (Acre-ft) Inactive and/or dead	Storage (Acre-ft) Total	Dam dimensions Ht (ft)	Dam dimensions Width (ft)	Reservoir area (acres)	Use	Applicant or owner	Remarks
Mud Mountain Reservoir	Puyallup R. 19-7-17	402	106,000	0	106,000	425	700	1,200	F	Corps of Engrs.	Storage not retained.
Lake Tapps (White R. proj.)	White R. 20-5-8	(off-stream) (424)	[1]44,000	2,600	46,600	--	--	2,566	P	Puget Sound Power & Light	Res. not on main channel.

[1] Elev. 542.

STORAGE AND REGULATION

Natural Surface Storage

The total amount of storage in lakes and glaciers of the basin is not known, but surface areas can be used to provide at least a comparative indication of the amount of water that is stored. The total surface area of lakes is 10.5 square miles, of which 5.9 square miles consists of reservoirs. Glaciers in the basin are on Mount Rainier, and their surface area is about 24.7 square miles.

Reservoirs

The following discussions and tabulations of existing and potential reservoirs in the Puyallup Basin pertain to those reservoirs of 5,000 acre-feet capacity or larger. Existing reservoirs and potential storage damsites are shown in Figure 93.

Existing Reservoirs—Mud Mountain Dam provides 106,000 acre-feet of storage on the White River. The reservoir is kept empty most of the year and is used only for flood control. A large part of the flow of the White River is diverted into Lake Tapps (44,000 acre-feet active storage). Water from Lake Tapps is used to generate electric power at the Puget Sound Power & Light Company's Dieringer Plant after which it is returned to the White River. Approximately 20,000 acre-feet is withdrawn from Lake Tapps storage during January-March for power generation and is replaced in April and May. Detailed information on existing reservoirs in the basin is presented in Table 41.

Potential Storage Sites—Information on potential storage sites in the basin is presented in Table 42.

DIVERSIONS

The Puget Sound Power & Light Company diverts as much as 2,000 cfs from the White River about 1 mile east of Buckley for its hydroelectric plant at Dieringer on the White River. This diversion bypasses about 20 miles of the White River. A flow of 25 cfs is released below the White River diversion dam for fish attraction, transportation and operation of the trapping facilities.

The Puget Sound Power & Light Co. operates a second hydroelectric power generating plant near Electron. Water is supplied to this plant from the upper Puyallup River. About 400 cfs is diverted and

TABLE 42.—Potential storage sites in the Puyallup Basin

Map no.	Project name	T-R-S	River and mile	Proposed storage (1,000 acre-ft)	Drainage area (sq mi)	Remarks
1	Mowich #1	17-7-32	Mowich 6.5	--	23	
2	Mowich #1A	16-6-3	Puyallup 46	--	30	
3	Orting	17-5-4	Puyallup 27	25	131	At Electron
4	Mile 9.2	19-6-30 19-6-31	Carbon R. 9.2	--	87	
5	Fairfax	18-6-16	Carbon R. 15.4	98	81	
6	Deadman Flat	19-9-8	White R. 42		292	
7	Twin Cr.	19-8-1	White R. 40	20	--	
8	W. Fk. Mouth	19-9-33	W. Fk. White R. 3	--	38	
9	Huckleberry	18-10-16	White R. 56	--	101	
10	E. Fk. Rainier	17-10-10	White R. 61	--	78	
11	Lost Cr.	18-11-5	Greenwater R.	--	26	
12	Echo Lake	18-11-16	Greenwater R.	13.9	12	
13	White River	20-5-8	White R.	--	424	Increase in storage of 1,377 acre-ft.

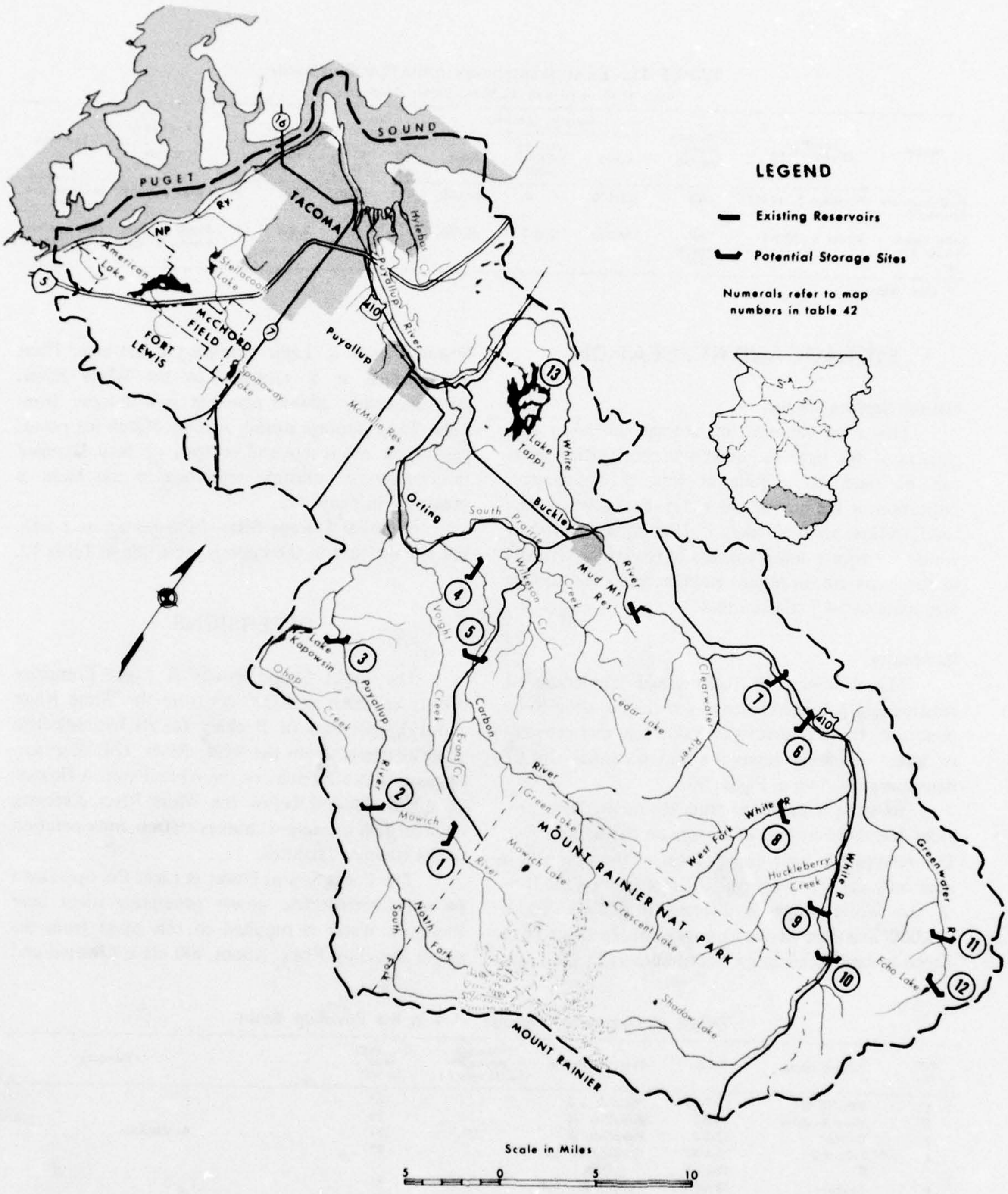


Figure 93. Existing Reservoirs and Potential Storage Sites in the Puyallup Basin

is returned to the river about 11 miles downstream from the diversion.

Three diversions of 5 cfs or more have been developed primarily for fish propagation in the Puyallup Basin. The State Department of Game operates a trout hatchery about 1 mile south of Puyallup through a diversion of 15 cfs from Maplewood Springs at the source of Clark Creek. The diverted water is returned to Clark Creek about 1,000 feet downstream from the point of diversion. Another hatchery about 2 miles southeast of Orting and operated by the State Department of Fisheries, diverts about 5 cfs from Voight Creek at a point about 1 mile above the hatchery. The flow is returned to Voight Creek a short distance above its confluence with Carbon River. A privately operated hatchery about a mile east of McMillan is entitled to divert 7.98 cfs from Canyon Falls Creek. This water is returned to the stream within a few hundred feet of the point of diversion.

The White River Lumber Company diverts about 5 cfs from Boise Creek near Enumclaw. Most of the water diverted is returned to the creek at a mill pond about half a mile downstream from the point of diversion.

Irrigation uses divert an estimated 8,200 acre-feet of water in the lower reaches of the White and Puyallup Rivers.

QUALITY OF SURFACE WATER

Chemical and Sanitary Quality

The surface water in the Puyallup Basin is generally dilute, soft, and suitable for most uses with little or no treatment. Quarterly and monthly samples collected from the Puyallup River at Puyallup contained 36 to 74 ppm dissolved solids (Table 58). The water was soft, maximum observed hardness was 40 ppm. The White River at Sumner is very similar chemically. The headwater reaches of the White and Puyallup Rivers and many of the tributary streams, contain water that is even softer and more dilute.

Water in the Chambers Creek basin is somewhat more mineralized than streams in the Puyallup Basin, probably because a larger percentage of the Chambers Creek flow is derived from ground water discharge. Chambers Creek and its tributaries Clover, Leach, and Flett Creeks were sampled monthly for 2 to 6 years (1962-67). Most of the samples contained less than 100 ppm of dissolved solids. However, dissolved solids in all of the samples collected from Flett Creek at Tacoma exceeded 100 ppm and hardness exceeded 60 ppm in 20 of 24 samples.

Turbidity may cause use problems in some of the streams in the Puyallup drainage. The Puyallup, Carbon, and White Rivers all receive very turbid glacial melt water during the summer months. Turbidities as high as 1,500 JTU have been recorded for the Puyallup River near Orting. This melt water is diluted by tributary inflow as it flows downstream. For example, the maximum recorded turbidity of the Puyallup River at Puyallup is 85 JTU. During the winter months the flow from the headwaters is much less turbid because of the greatly reduced melting of the glaciers; this winter flow actually dilutes the turbid storm runoff from the lower parts of the basin.

Sanitary quality of surface waters in the Puyallup drainage is typical of that of many western Washington basins. Coliform values are usually low in the upper reaches of the stream, and they increase in a downstream direction, particularly where the lower parts of the basin are highly populated. For example, the MPN of coliform bacteria in the Puyallup River near Orting is usually less than 100, although values up to 2,400 have been recorded at this site. Downstream, at Puyallup, MPN values range from 0 to 24,000, with a mean of more than 5,000 (Table 58).

Chambers Creek drains parts of south Tacoma and the suburban and agricultural lands to the south. Sanitary quality in the stream varies from good to poor. The MPN values of coliform bacteria in Clover Creek above Parkland are usually less than 100 but occasionally as high as 430. Chambers Creek below Steilacoom Lake carries water of similar sanitary quality. However, Leach Creek near Steilacoom has MPN values usually in excess of 400 and occasionally more than 4,500. Flett Creek, at Tacoma, has an average annual MPN value in excess of 7,000. Nitrate and phosphate, often associated with sanitary wastes, are more concentrated in the Chambers Creek drainage than would be expected to occur naturally. Monthly samples from Flett Creek at Tacoma contained 6.8 to 13 ppm nitrate over a 1-year period and one sample contained 0.98 ppm phosphate. Such large amounts of nutrient could stimulate algae blooms in these streams and produce a further deterioration in water quality.

Stream Temperatures

Spot observation of temperature records from stations on the Puyallup River near Orting and

Puyallup, and from a station on the White River near Sumner, are listed in Table 59. In addition, a short-term thermograph record is available for the Puyallup River near Puyallup.

The temperature of the Puyallup River at Orting is relatively low (less than 60°F during the warmest months) reflecting the glacial origin of the stream. The increase in heat content of the stream at Puyallup, most noticeable in the summer, doubtless is caused by the contribution of relatively warm water from the White River. The summer flow in the White River near Sumner has attained a temperature as high as 73°F.

The White, like the Puyallup, is a glacier-fed stream and its temperature, therefore, should be about the same. The observed temperature difference can be explained by the relatively small volume of flow of the White near Sumner. As pointed out earlier, the smaller the flow the more easily will the temperature be influenced by ambient heat conditions. As a result of this difference, temperatures at Puyallup (below the confluence of the White) should be expected to be intermediate to those at Sumner and Orting stations, respectively.

Sediment Transport

The upper drainage in the basin consists of watersheds in the White, Carbon, and Puyallup basins that are upstream from Buckley, Carbonado, and Electron; the lower drainage is in the remaining areas downstream. In the upper drainage, the rivers flow through mountainous terrain and traverse narrow stream valleys or canyons that are deeply entrenched in glacial drift. Soils in the upper drainages are extremely variable in physical character. On steep slopes they are thin and stony, and along the streamchannels they are identified as loam derived from gravelly glacial drift. Thick vegetal cover prevents soil erosion, except where it has been removed by man.

Although much of the suspended sediment carried by both rivers is derived from glaciers, the White River transports more sediment than the Puyallup. Analysis of data obtained for the White River near Greenwater indicates that suspended sediment concentrations range from 10 to 60,000 ppm. Discharge of the stream at this site varies considerably, and the distribution of sizes of suspended particles change with the discharge. In one day the distributions of particle sizes were observed to range from 8 to 18% clay, 34-65% silt, and 16-56% sand. Streams which are not fed by glaciers generally have suspended-sediment concentrations less than 10 ppm. Because of fairly high stream gradients in the upper drainage, the movement of streambed materials, principally cobbles and large boulders, is considerable during high runoff.

In the lower drainage, the streams traverse flood plains that are bordered by upland areas of steep or broken relief. On the flood plains the soils are derived from recent alluvium and are quite permeable. On the bordering uplands the soils are derived from loose gravelly drift and are well drained. Where the vegetal cover is dense or compact, erosion of soil is largely prevented. Some channel erosion has occurred in the lower drainage, but the magnitude has been stemmed in a few urban areas as a result of channel improvements. On the basis of data obtained during 1965-66, instantaneous sediment load in the Puyallup River ranges from about 1 to 27,100 tons per day. When the average daily discharge reaches 22,000 cfs, a rate reached only during an infrequent flood, the Puyallup River at this site may transport as much as 380,000 tons of sediment per day. The river probably transports more than a million tons of suspended sediment during a year of normal streamflow. A particle-size analysis for the White River near Sumner indicates that the suspended sediment is composed of about 8% clay, 22% silt, and 70% sand.

Sediment problems in the basin occur locally where logging, construction, or farming has resulted in erosion. Some usable land adjacent to rivers has been lost owing to sloughing of banks. The deposition of sediment in reservoirs and at the mouth of the Puyallup River has caused some problems.

GROUND WATER

Ground-water supplies are plentiful in much of the lowlands of the Puyallup Basin; supplies can be developed locally in the mountains where Quaternary deposits occur. The lowlands lie generally west of Electron and Mud Mountain Reservoir, and the mountains are considered as the remaining areas to the east.

LOWLANDS

Geology and Ground Water Occurrence

The important aquifers in the lowlands occur in coarse Quaternary sediments; these deposits are nearly continuous over about 420 square miles. Locally, near Puget Sound, Quaternary deposits exceed 2,000 feet in thickness. Fresh-water aquifers exist at depths as great as 1,500 feet below sea level, but water is pumped mainly from aquifers less than 500 below sea level. Ground-water can be obtained from depths less than 100 feet below land surface in most places.

Quaternary sediments exposed at the surface are mainly till, recessional outwash, alluvium, and mudflow deposits. The uplands northeast of a line through Fircrest and Orting are underlain by till, which is mantled by isolated deposits of recessional outwash. The till is normally less than 30 feet thick, but locally its thickness may exceed 60 feet. The till is breached and truncated along bluffs that border Puget Sound and the more deeply incised valleys. Till is locally absent beneath recessional outwash benchlands in the southwestern part of the basin. Because it is composed largely of fine compacted materials, the till is not an important aquifer even though it is somewhat permeable.

Recessional outwash is extensive in the southwestern part of the basin. It consists predominantly of sand and gravel and is generally less than 50 feet thick, but locally it may be more than 200 feet thick. Although recessional outwash is at least partly saturated in the southwestern part of the basin, the saturated interval in many places is not adequate to support large well yields.

Alluvium occurs mainly on the White River flood plain from Auburn to Sumner and on the Puyallup River flood plain from Orting to Commencement Bay. Upper zones in the alluvial materials contain silt, clay, and fine sand of low permeability. The alluvial deposits are at least 200 feet thick at Sumner, but at the mouth of the Puyallup River their thickness probably exceeds 500 feet. Upstream from Sumner, the alluvium thins but contains coarser materials. Alluvium is generally saturated to about river level, but the deeper alluvial aquifers are confined under artesian pressure. Alluvium may everywhere contain zones that yield appreciable quantities of water to wells. In the Puyallup Valley below Sumner, however, some of the deep wells with substantial yields may also obtain water from older Quaternary units.

A recent mudflow from the slopes of Mount Rainier mantles the plateaus on both sides of the White River valley between Lake Tapps and Mud Mountain Reservoir. Both recessional outwash and till are covered by the mudflow in that area. The mudflow deposits are apparently less permeable vertically than till, and they confine water in underlying aquifers of recessional outwash. Thickness of the mudflow varies locally, but it is not known to exceed 75 feet.

Quaternary sediments older than the till are exposed in only a few places; their outcrops are mainly on the steep slopes that border Puget Sound and the flood plains of the White and Puyallup Rivers. These older sediments at most places contain sand and gravel aquifers that commonly are more than 100 feet in aggregate thickness. Locally, the aquifers yield substantial amounts of water to wells. Generally the aquifers are confined under artesian pressure except at higher altitudes, where upper zones are locally above the water table.

Practically all recharge to the aquifers in the lowlands—even those overlain by till or mudflows—is by infiltration of precipitation. Aquifers in the lowlands of the Puyallup Basin may receive about 130,000 acre-feet of recharge annually on the average. Opportunities for induced (natural) recharge are favorable in areas along the flood plain of the White River, but surficial alluvial deposits along the Puyallup River generally are rather fine and, therefore, would not accept much recharge. Some of the water-table lakes in recessional outwash in the southwestern part of the basin, on the other hand, might provide favorable areas of artificial recharge in the event of significant lowering of the water table.

The natural discharge of ground water is mostly into the White and Puyallup Rivers and their tributaries and into Puget Sound through springs above and below the tidewater level.

Quality of Ground Water

Most of the aquifers now being developed contain water that is low in dissolved solids and is acceptable for practically all uses. Dissolved-solids content in most water is less than 200 ppm. Hardness of water generally does not exceed 60 ppm. Measured silica concentrations range from 7 to 54 ppm, and average about 30 ppm. Objectional concentrations of

iron occur locally, principally in aquifers that underlie the Puyallup and White River flood plains. In the flood-plain area of the lower Puyallup River, sodium concentrations are rather high, generally exceeding 50 ppm in most of the basin.

Utilization and Development

Most of the ground-water currently developed in the basin is used for public supply, principally in the Tacoma area. Of the public-supply ground-water systems active in the basin in 1967, only the Tacoma municipal supply depends, in part, on surface water.

The largest system, exceeding 40,000 gpm, is operated by the City of Tacoma and is used to supplement the city's principal source of water, the upper Green River. Public-supply systems of Puyallup, Enumclaw, and Sumner, use water from springs. Most industrial wells in the basin are within the city limits of Tacoma. A rather large development of ground water for industry is in the tide-flats area along Commencement Bay. Most irrigation wells are on the flood plains of the Puyallup and White Rivers.

The large-capacity wells pump water from aquifers older than recessional outwash. The largest well yields have been obtained in the South Tacoma area, where individual wells pump more than 3,000 gpm, and calculated coefficients of transmissibility are locally as high as 2 million gallons per day per foot.

Figure 23 shows order-of-magnitude estimates of expected well yields in the Study Area. The largest well yields are apparently obtainable from subtill aquifers in the South Tacoma area and from deep aquifers in the Puyallup River valley. Alluvium in the White River valley also appears capable of supporting large-yielding water wells. Some wells that tap aquifers beneath flood plains of the White and Puyallup Rivers and lowlying areas adjacent to Puget Sound are known to flow.

MOUNTAINS

In the mountains, sand and gravel aquifers probably occur in Quaternary sediments that cover about 30 square miles bordering the Puyallup and Mowich Rivers. Abundance of precipitation suggests the aquifers may receive relatively large amounts of recharge. Provided aquifers having adequate saturated thickness and permeability can be located in the Quaternary deposits, it might be possible to develop substantial ground-water supplies on a sustained basis. Elsewhere in the mountainous areas ground-water is obtainable only from consolidated and semiconsolidated rocks, which yield 10 gpm or less to wells.

NISQUALLY—DESCHUTES BASINS

SURFACE WATER

The Nisqually-Deschutes Basins (Figure 102) comprises 1,044 square miles including 1,008 square miles of land and inland water.

The principal rivers in this area are the Nisqually with a drainage area of 712 square miles, and the Deschutes, which drains 162 square miles.

The Nisqually River has a length of 81 miles and originates at the glaciers on the southwestern slopes of Mount Rainier. From its origin at the foot of Nisqually Glacier at an altitude of 4,600 feet, to the western boundary of Mount Rainier National Park, the Nisqually River flows southwesterly and westerly through steep mountainous valleys with timbered slopes. From the park boundary to its confluence with Little Nisqually River at the lower end of Alder Reservoir, the river flows northwesterly for 26 miles and falls at the rate of 40 feet per mile. The river then enters LaGrande Canyon, a deep narrow gorge, through which it flows for 3 miles with a gradient of 135 feet per mile. Below LaGrande Canyon, the river flows 41 miles over a benchland of glacial moraines to Puget Sound, midway between Tacoma and Olympia.

The Deschutes River, having a length of 35 miles, heads in the hills southeast of Yelm and flows across benchlands into Bud inlet, the southernmost arm of Puget Sound, at Olympia. The river parallels the lower part of the Nisqually River, and occupies a part of the benchland common to both streams.

STREAMFLOW

Runoff Characteristics

Runoff from the southwestern slopes of Mount Rainier in the source area of the Nisqually River basin is estimated to average in excess of 120 inches annually. The runoff contribution decreases rapidly below these headwaters to a minimum of about 15 inches in the lowlands near the mouth. The estimated average runoff per year from the 751 square miles in the basins is about 36 inches, or 1,900,000 acre-feet.

Flows for the Nisqually River near National (Figure 94) indicate a mean annual discharge of 741 cfs or 537,000 acre-feet during the 30-year period 1931-60. This is equivalent to a unit runoff of 5.6 cfs per square mile.

For the period of record, a maximum yearly discharge of 991 cfs in the Nisqually River near National occurred during the 1956 water year. This is approximately 134% of the adjusted 30-year mean for the 1931-60 period. The minimum yearly discharge of record occurred in the water year 1944 and amounted to 67% of the 30-year mean.

Natural runoff patterns for Nisqually River near National parallel those found in the adjacent Puyallup River drainage (Figure 95). Two distinct peak periods occur each year, one from abundant winter precipitation falling mainly in the form of rain at lower elevations, and the second in May and June primarily from the melting of accumulated high elevation snowpacks. The low-flow period occurs in August and September, but large quantities of glacial melt water from the slopes of Mount Rainier make a significant contribution to summer flows during these warm months.

With the exception of the headwater area, the Deschutes River drains a rather narrow, poorly defined basin in the southern Puget Sound lowlands. Annual runoff in the upper reaches of this watershed probably exceeds 80 inches as an average. The glaciated lowlands, however, yield only about 20 to 30 inches of runoff annually.

For the period, 1931-60, the mean annual discharge from headwater areas in this watershed above the gaging station near Rainier is 253 cfs or 183,000 acre-feet. This amounts to 2.8 cfs per square mile from the 90.8 square-mile drainage area. At the gaging station near Olympia the mean annual runoff was 388 cfs or 281,000 acre-feet. The unit runoff is 2.4 cfs per square mile. In general, the runoff production of the Deschutes River basin is comparable to that of the lowlands in the southern parts of the West Sound Basins.

Variations in annual runoff (Figure 96) follow trends similar to those found in other southern Puget Sound drainages. However, a comparison of annual runoff for the Deschutes River and Skagit River shows that in some years the trends differ somewhat between the northern and southern parts of the Puget Sound Area. The periods of record at both stations on the Deschutes River are fairly short, so the recorded maximum and minimum average yearly discharges are probably not indicative of maximum and minimun conditions that might be expected from

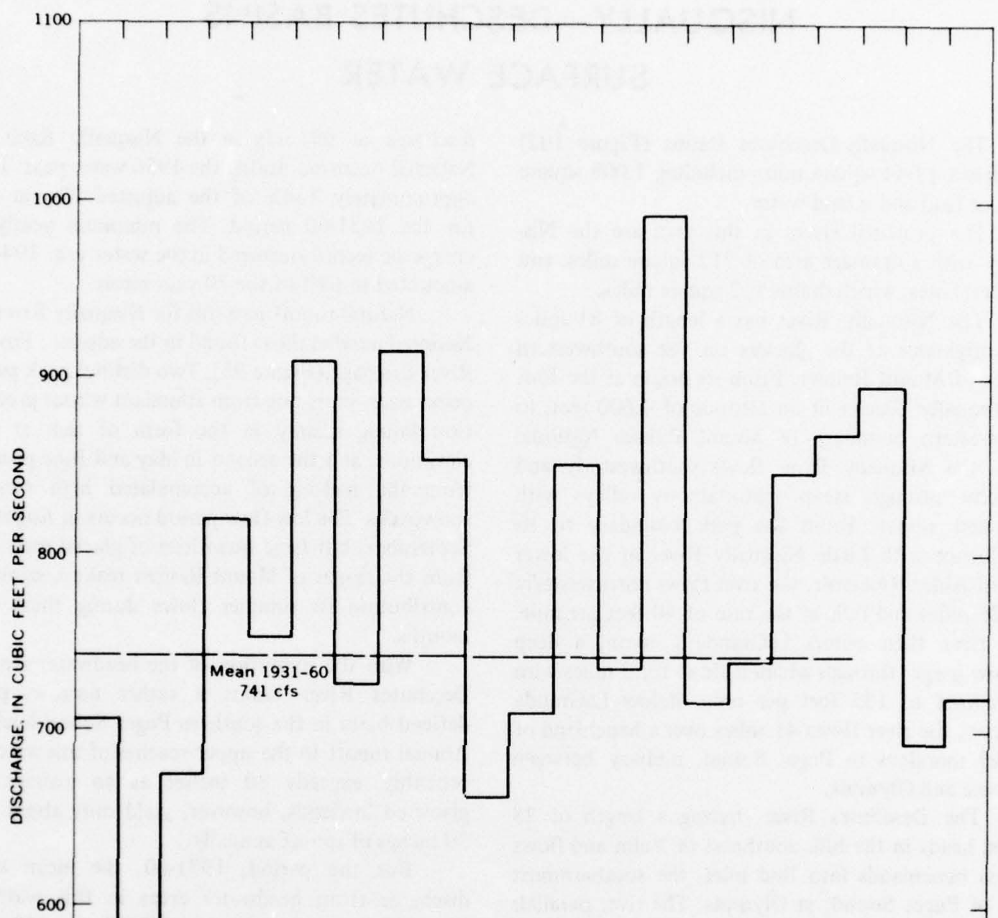


FIGURE 94.–Annual discharges, Nisqually River near National.

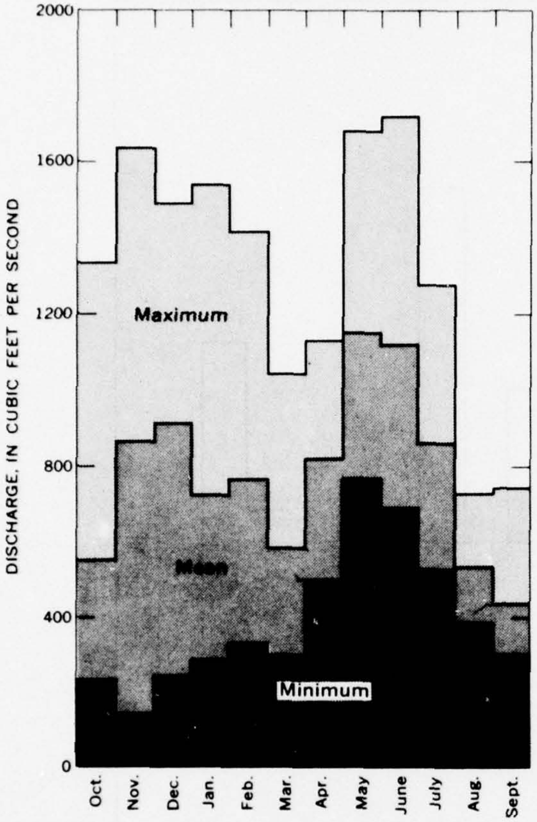


FIGURE 95.—Maximum, mean and minimum monthly discharges, Nisqually River near National 1931-60.

long-term records. Since 1946, when record collection began at the station near Olympia, the minimum annual flow has been 279 cfs. This occurred during the 1962 water year, and amounts to 72% of the estimated 30-year mean flow. Although records were not collected at the downstream Olympia gage for the entire 1955-57 water years, the upper gage indicates that the maximum annual discharge since 1946 occurred during water-year 1956 and was about 153% of the adjusted 30-year mean flow.

Mean monthly discharges for the Deschutes River display the same pattern as those for other primarily rain-fed streams of the southern Puget Sound lowlands (Figure 97). Normally one extended period of high flows occurs during the winter season, with the possibility of monthly peak flows in December, January, or February.

Minimum flows, derived primarily from ground-water discharge, are most probable during August and September.

Hydrograph characteristics in the basins were analyzed for the Nisqually River near National and the Deschutes River near Olympia. The Nisqually gage measures approximately 70% of the runoff of the Nisqually basin and the Deschutes gage measures about 99% of that basin's runoff.

Flow of the Nisqually River near National usually begins to increase in October from summer base flow of about 400 cfs. Streamflow during the period October to March is characterized by a series of sharp rises superimposed on a base flow, which is highest in December. Runoff generally decreases from December through March as a result of reduced rainfall. As temperatures begin rising in April, snowmelt causes an increase in streamflow, which characteristically reaches a daily flow of about 1,300 cfs in May. Following the snowmelt peak, streamflow recedes to minimum base flow by August or September as the snowpack is depleted. At this time discharge is sustained by contributions from ground-water storage and glacial melt water.

Streamflow on the Deschutes River near Olympia usually begins to increase in October from the summer base flow of about 100 cfs. During the period October to March, the discharge is characterized by a series of sharp rises superimposed on an increasing base flow. Runoff in the period March to July decreases as a result of reduced precipitation. Minimum base flow is usually reached by the first part of August. Variability of the daily flows of streams in the basins is presented as flow-duration data for selected gaging stations in Table 43.

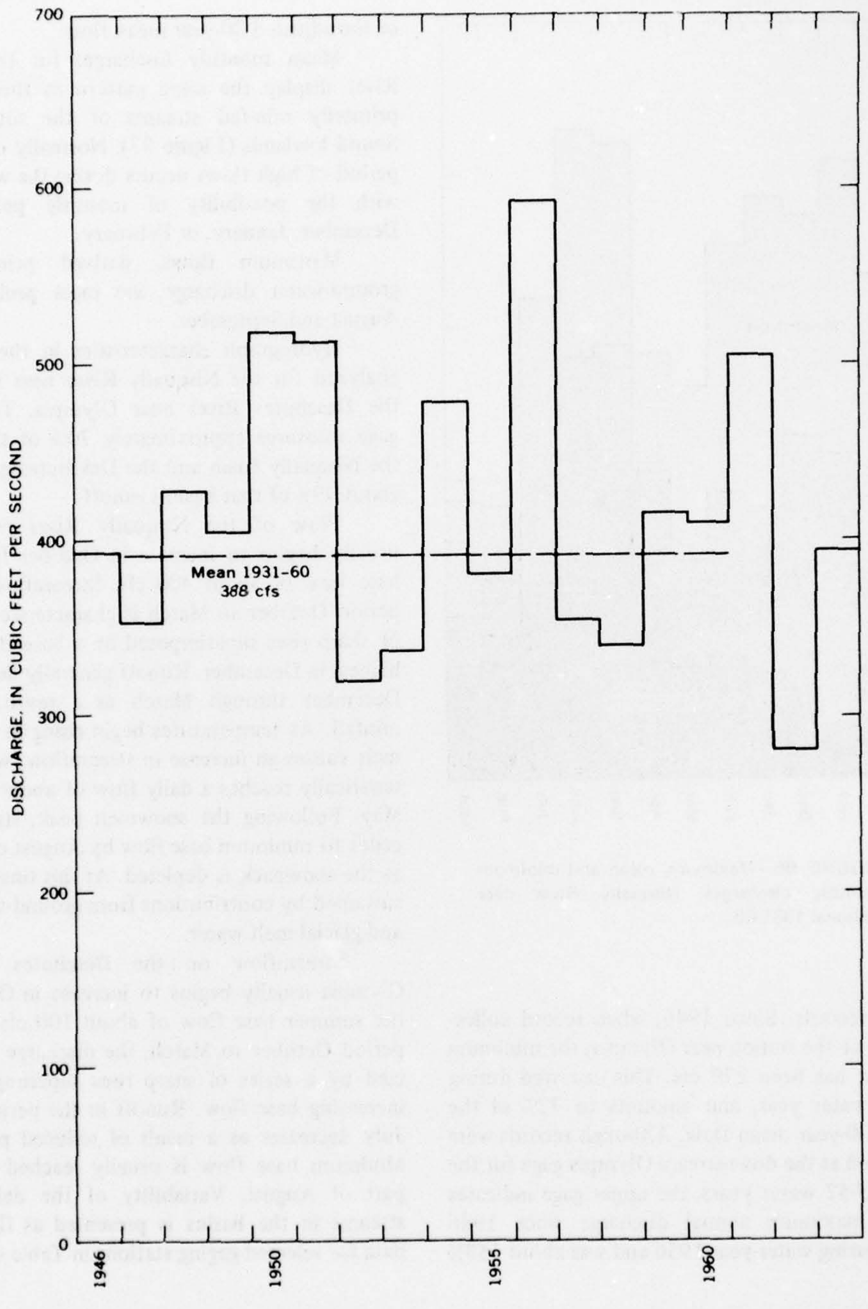


FIGURE 96.–Annual discharges, Deschutes River near Olympia.

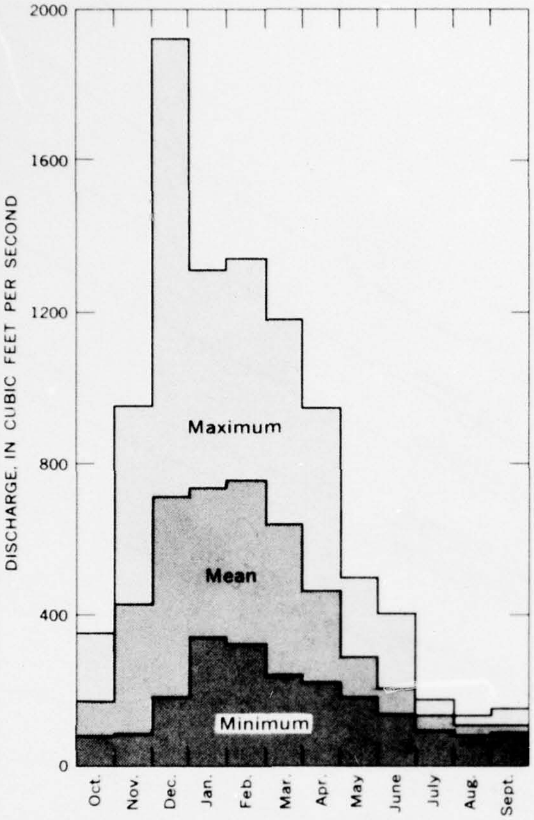


FIGURE 97.—Maximum, mean and minimum monthly discharges, Deschutes River near Olympia, 1931-60.

Flood Characteristics

Floods caused by high rainfall and accompanying snowmelt in the Nisqually basin are shown by characteristic sharp rises on a hydrograph followed by recessions almost as rapid. Two or more flood peaks often occur within a period of 2 weeks.

The maximum discharge recorded for the Nisqually River near National was 10,900 cfs on November 23,1959. A maximum discharge recorded for the Deschutes River near Olympia was 6.650 cfs, and occurred on January 23, 1964.

Flood-frequency curves for Nisqually River near National and Deschutes River near Olympia are presented in Figures 98 and 99. The 22-year record for the Nisqually River near National is 1943-64. Frequency statistics at this site were extended to an equivalent period of 36 years by correlation with the South Fork Skykomish River near Index, which has a record period of 54 years. The period of record for the Deschutes River near Olympia is 1946-64, 18 years.

TABLE 43.—Flow-duration data for streams in the Nisqually-Deschutes Basins

Gaging station	Period of analysis	Flow, in cubic feet per second, which was equaled or exceeded for indicated percent of time											
		99	95	90	80	70	50	30	20	10	5	1	0.1
Deschutes River near Rainier	1950-64	27	32	37	47	68	154	278	392	630	920	1,830	3,100
Deschutes River near Olympia	1946-54, 1958-63	78	91	101	121	147	266	440	600	900	1,230	2,120	3,600
Woodland Creek near Olympia	1950-61	9.0	10	12.5	15	17.5	23	32	39	53	70	96	133
Nisqually River near National	1943-64	195	275	325	405	475	640	880	1,060	1,380	1,710	2,740	4,900
Mineral Creek near Mineral	1943-64	25	34	42	63	110	155	440	580	840	1,150	2,250	4,000
East Creek near Elbe	1919-22, 1950	2.2	3.2	3.8	5.8	15	33	60	84	135	220	540	1,150
Nisqually River near Alder	1932-44	203	312	395	500	600	850	1,250	1,570	2,170	2,900	5,800	12,400
Little Nisqually River near Alder	1921-26, 1930-42	4.8	6.6	8.4	13	23	55	111	166	284	440	970	1,750
Mashel River near LaGrande	1941-57	9.5	14	19.5	38	68	145	255	350	520	740	1,450	2,900
Ohop Creek near Eatonville	1928-32 1942-64	4.5	6.5	8.7	14	22	45	78	104	150	204	360	680
Tanwax Creek near McKenna	1946-50	1.0	1.3	1.6	2.5	4.9	19	43	58	86	108	200	320
Muck Creek at Roy	1957-64	0	0	.25	2.0	5.4	30	79	112	165	215	330	500

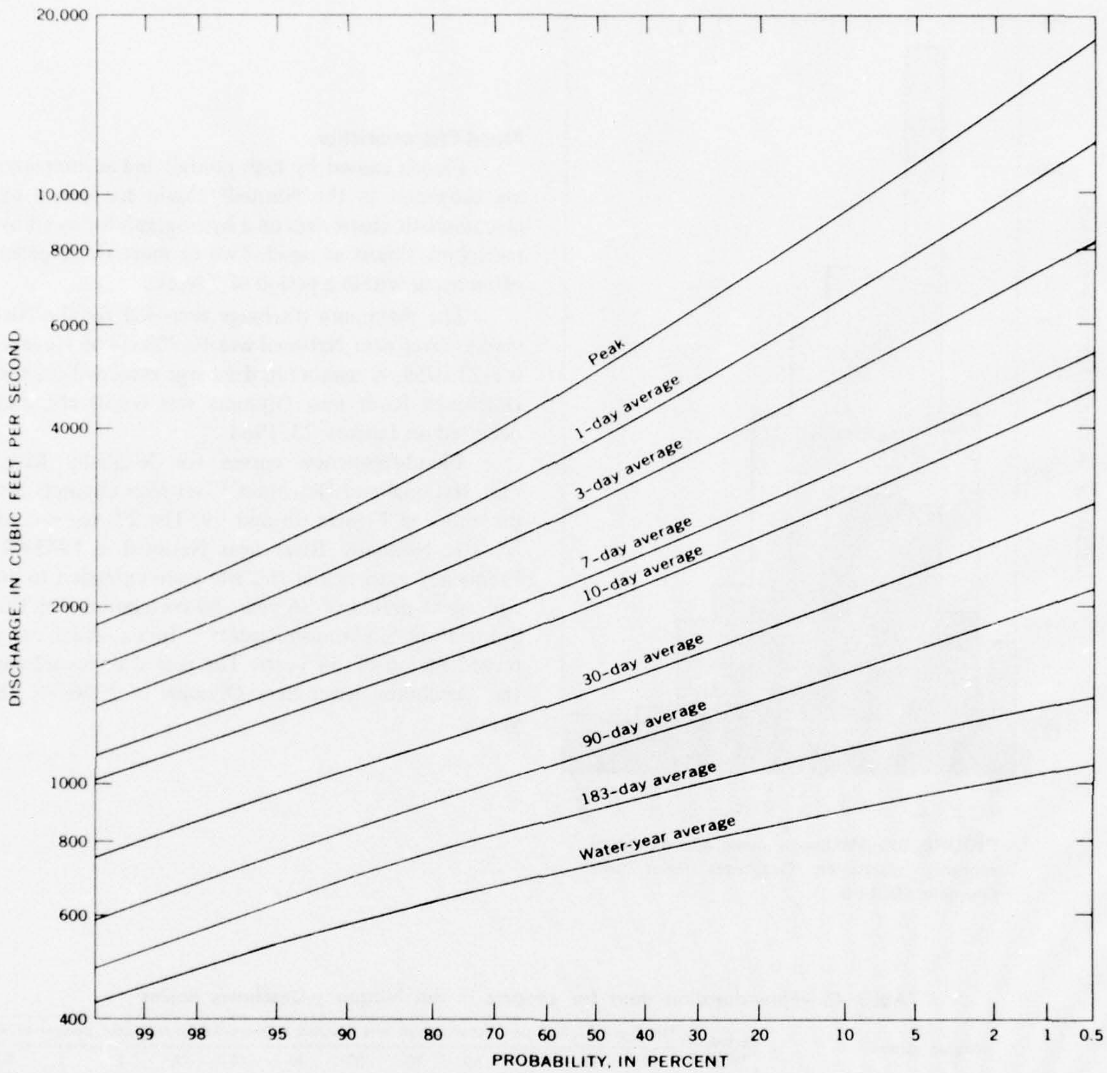


FIGURE 98.—Probability curves of annual maximum flows for specified time periods, Nisqually River near National.

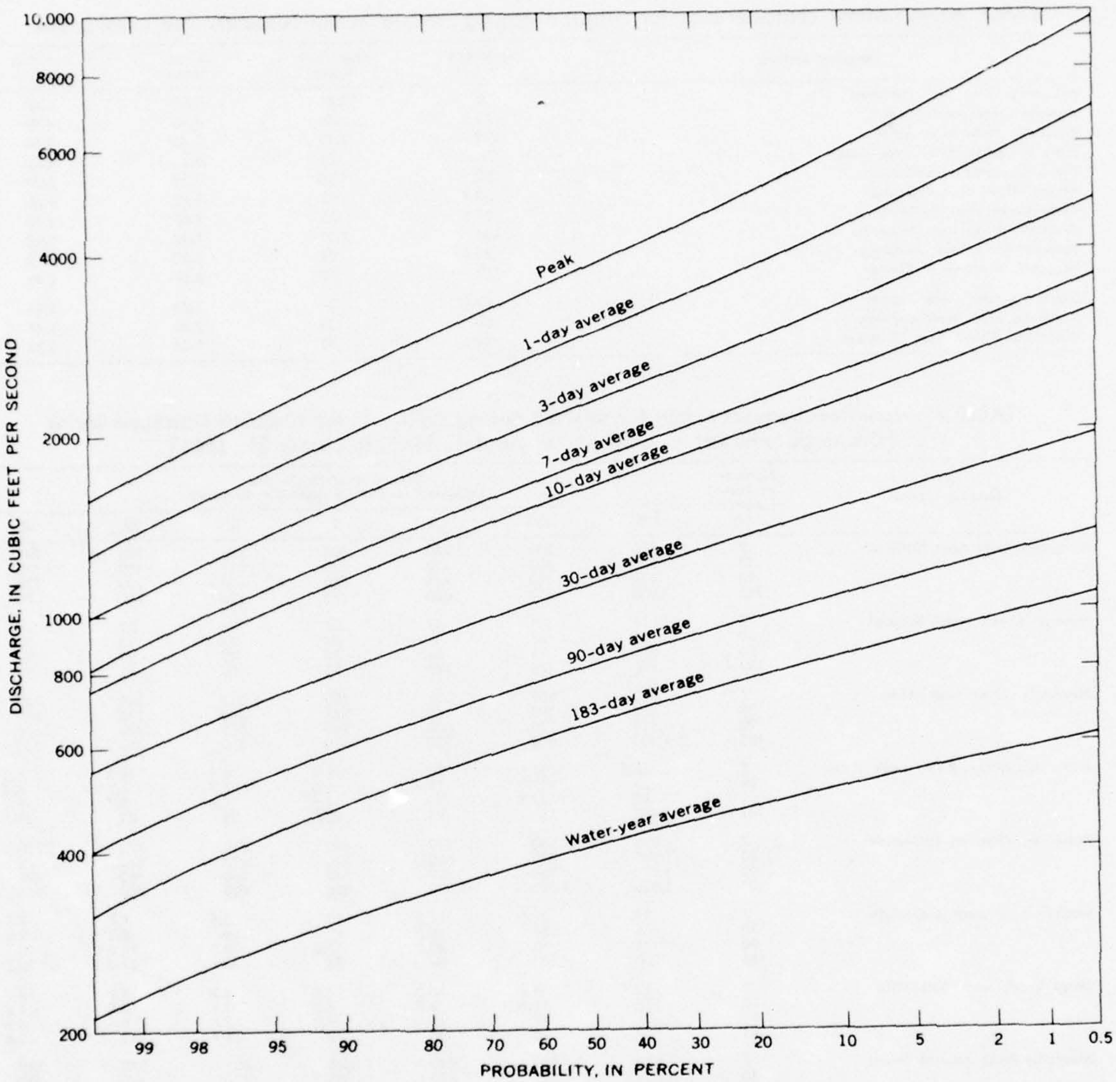


FIGURE 99.–Probability curves of annual maximum flows for specified time periods, Deschutes River near Olympia.

TABLE 44.—Low-flow characteristics for selected gaging stations in the Nisqually-Deschutes Basins

Gaging station	Drainage area	Low flow index	Slope index	Spacing index
Nisqually River near National	133	1.88	1.59	2.40
Mineral Creek near Mineral	75.2	.44	1.43	4.40
Nisqually River near Alder	249	1.41	1.45	2.34
Little Nisqually River near Alder	28.0	.36	1.72	4.40
Nisqually River at LaGrande	292	1.78	1.33	2.00
Mashel River near LaGrande	80.7	.18	1.92	6.40
Ohop Creek near Eatonville	34.5	.19	1.67	4.15
Nisqually River near McKenna	445	1.21	1.45	2.20
Tanwax Creek near McKenna	26.0	.04	1.75	5.72
Nisqually River at McKenna	517	.32	6.67	4.49
Deschutes River near Rainier	89.8	.36	1.28	2.56
Deschutes River near Olympia	160	.60	1.28	1.67
Woodland Creek near Olympia	24.6	.51	1.56	1.36

TABLE 45.—Low-flow frequency data for selected gaging stations in the Nisqually-Deschutes Basins
[*Discharge adjusted to base period April 1, 1946, to March 31, 1964*]

Gaging station	Number of consecutive days	Stream flow in cfs, for indicated recurrence intervals, in years						
		1.05	1.30	2.0	5	10	20	30
Nisqually River near National	7	360	300	250	202	178	156	147
	30	490	385	320	250	213	188	173
	90	610	510	445	380	350	330	320
	183	1,000	760	600	475	420	380	370
Mineral Creek near Mineral	7	59	41	33	26	24	22	21
	30	68	47	38	30	27	25	24
	90	113	73	54	38	32	28	27
	183	290	198	145	96	76	62	55
Nisqually River near Alder	7	490	405	350	290	263	240	230
	30	590	505	445	375	340	310	290
	90	850	720	630	540	505	480	465
	183	1,200	960	820	680	610	560	530
Little Nisqually River near Alder	7	22.5	13.8	10	7.3	6.4	5.8	5.5
	30	28	17.5	12.7	9.0	7.7	6.8	6.4
	90	42	27.5	20	13.9	11.4	9.7	9.0
	183	102	63	44	30.5	25	21	19.5
Nisqually River at LaGrande	7	890	650	520	430	410	390	380
	30	1,050	810	660	520	470	440	420
	90	1,200	960	800	640	560	500	470
	183	1,520	1,220	1,040	880	820	780	750
Mashel River near LaGrande	7	39	21.6	14.7	10	8.6	7.7	7.3
	30	56	29	18.5	12	10	8.8	8.3
	90	93	50	30.5	17.8	13.8	11.3	10
	183	200	135	94	54	38	27.5	22.8
Ohop Creek near Eatonville	7	12.7	8.6	6.5	4.9	4.3	3.9	3.7
	30	16	11.6	8.9	6.6	5.7	5.0	4.6
	90	24	17	13	9.2	7.6	6.4	5.8
	183	59	38	27	18	14.4	12	10.8
Nisqually River near McKenna	7	800	640	540	445	405	375	360
	30	1,020	820	690	560	500	455	430
	90	1,270	1,000	830	660	590	540	510
	183	1,740	1,400	1,190	990	900	840	800
Tanwax Creek near McKenna	7	2.5	1.5	1.05	.76	.66	.60	.58
	30	3.6	2.1	1.4	.95	.80	.70	.66
	90	6.7	3.5	2.3	1.5	1.2	1.0	.92
	183	14.7	8.8	6.0	3.6	2.8	2.2	1.9
Nisqually River at McKenna	7	530	295	167	72	42	25	19
	30	750	460	280	132	83	53	42
	90	990	610	415	255	195	150	130
	183	1,480	1,030	750	540	480	460	450
Deschutes River near Rainier	7	40	35	32	28	26	25	24
	30	46	39	35	31	29	27	26
	90	60	49	41	35	32	30	29
	183	121	99	82	62	52	44	40
Deschutes River near Olympia	7	123	107	96	85	80	75	72
	30	132	114	101	89	83	79	76
	90	148	126	110	96	88	82	79
	183	220	187	160	130	115	102	96
Woodland Creek near Olympia	7	19.7	15.2	12.5	9.9	8.8	8.0	7.6
	30	21.2	16.7	13.5	10.9	9.7	8.9	8.5
	90	22.5	17.7	14.5	11.5	10.2	9.2	8.9
	183	27	21	17	13.2	11.7	10.3	9.8

Low-Flow Characteristics

Low-flow characteristics of streams in the Nisqually-Deschutes Basins are compared using indexes from low-flow frequency curves at 13 gaging stations (Table 44). The low-flow indexes are excellent in the upper Nisqually Basin and are fair in the lower Deschutes Basin (Fig. 22). The remainder of the study area has poor indexes. Except for the lowest station on the Nisqually River, which is affected by diversion and regulation, the slope and spacing indexes, which show the variability of low flows, do not differ appreciably. The Deschutes River has the smallest index and the Mashel River has the largest. Low-flow frequency data for the 13 stations are listed in Table 45. Frequency curves for 2 of the 13 stations are shown in Figures 100 and 101.

In the Nisqually Basin all streamflow records used are from stations in the upper watershed. Regulation of the Nisqually River at Alder Lake and LaGrande Reservoir affects the flow at the three gaging stations downstream. The records of the Nisqually River at McKenna are also affected by diversion to the Centralia Power Canal. All other records in the Nisqually-Deschutes Basins represent natural runoff conditions.

Low-flow indexes in the basins range from 0.04 cfs per square mile for Tanwax Creek to 1.88 for the Nisqually River near National. The large contributions, principally from glaciers, from the upper basin result in large indexes for all the Nisqually River main-stem stations except at McKenna (some streamflow is diverted around the McKenna station). Tanwax Creek, Ohop Creek, and Mashel River, which are tributaries to the Nisqually River from the north have the smallest values—less than 0.20 cfs per square mile. The southern tributaries, Mineral Creek and Little Nisqually River, have slightly higher indexes—about 0.40 cfs per square mile.

In contrast to the areal pattern of low-flow indexes in the Nisqually Basin, the Deschutes Basin has smaller indexes in the upper part of the basin than in the lower part. The low-flow index in that basin increases from 0.36 cfs per square mile near Rainier to 0.60 cfs per square mile near Olympia reflecting ground-water contributions between the two stations. The index for Woodland Creek basin is about 0.51 cfs per square mile, which is similar to that of Deschutes River basin.

Slope indexes for all but one station in the Nisqually Basin range from 1.33 for Nisqually River above LaGrande, to 1.92, for Mashel River. An anomalous value of 6.67 for the Nisqually River at McKenna is due to regulation and diversion. Regulation of low flows at Alder Lake and LaGrande Reservoir is responsible for the small index for Nisqually River at LaGrande. The uniform nature of low flows along the main stem of the Deschutes is indicated by the slope index of 1.28 at both the Rainier and Olympia stations, which is lower than average for the Puget Sound Area. The slope index of 1.56 for Woodland Creek is also lower than average.

Spacing indexes in the Nisqually Basin have the same general areal variations as slope index. Spacing indexes of 2.00 and 6.40 were determined for Nisqually River above LaGrande and for Mashel River, respectively. The small indexes for the Nisqually River main stem stations, which are smaller than those for the tributaries, may be attributed to the glacial source of the river and the prolonged snowmelt from high-altitude areas of the upper watershed. The impervious nature of surface materials in the Mashel River basin is reflected in the large spacing index for this stream.

In the Deschutes Basin, spacing indexes are 2.56 at Rainier, 1.67 at Olympia, and 1.36 for Woodland Creek. The larger index at the Rainier site indicates the effects of rather impervious surface materials in the watershed whereas the smaller index at Olympia may be due to the influence of ground-water contributions from alluvial and outwash materials in the lower valley.

STORAGE AND REGULATION

Natural Surface Storage

The total amount of storage in lakes and glaciers in the basins is not known, but the surface area covered by these waters provides at least a comparative indication of the amount of water that is stored.

The total lake surface is 12.6 square miles of which 4.9 square miles consists of reservoirs. Glaciers in the basins are on the slopes of Mount Rainier, in the Nisqually watershed, and total 5.6 square miles in area.

Reservoirs

The following discussions of existing and potential reservoirs in Nisqually- Deschutes Basins are restricted mainly to those of 5,000 acre-feet capacity, in size. Existing reservoirs and potential storage sites in the basins are shown in Figure 102.

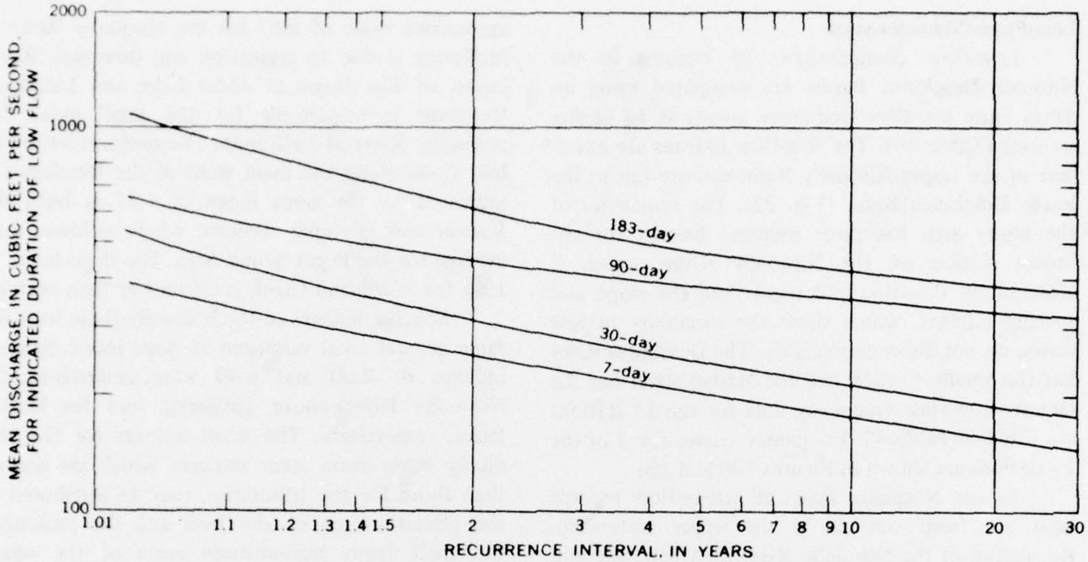


FIGURE 100.—Low-flow frequency, Nisqually River near National, 1946-63.

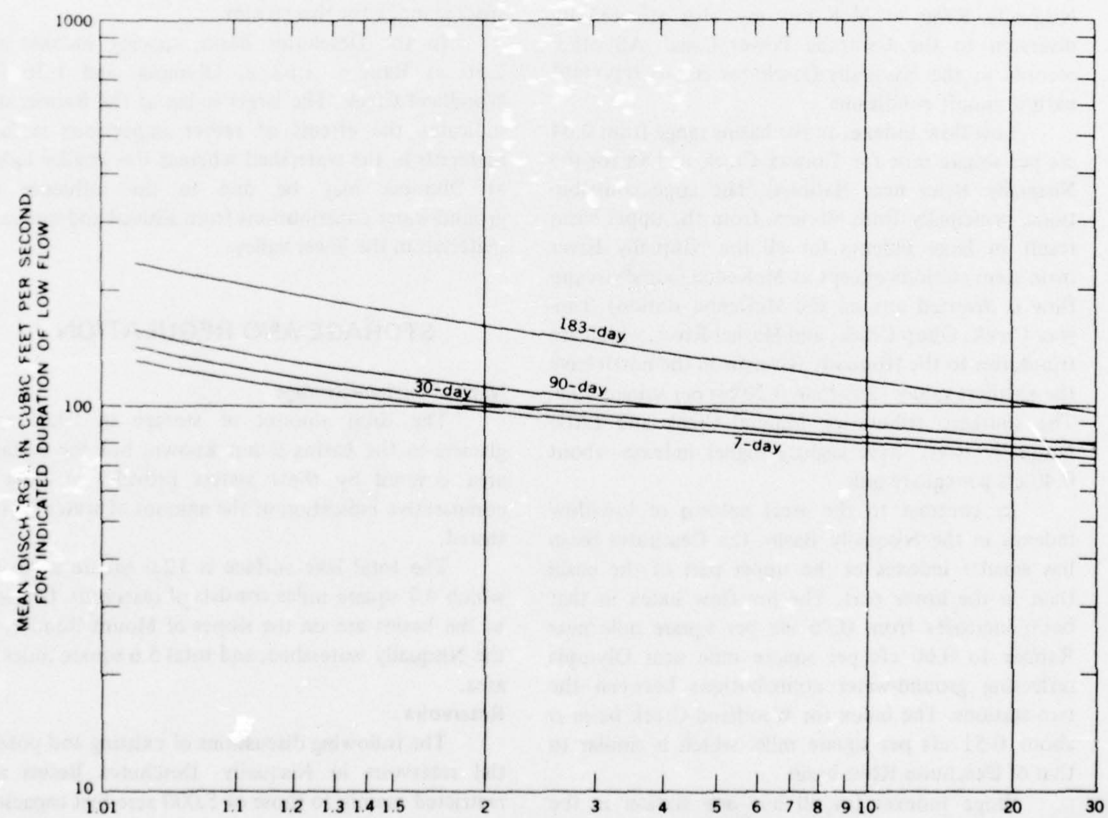


FIGURE 101.—Low-flow frequency, Deschutes River near Olympia, 1946-63.

TABLE 46.—Existing reservoirs in the Nisqually-Deschutes Basins

Use: P. Hydro-electric development

Name	Location Stream, T-R-S	Drainage area (sq mi)	Storage (acre-ft) Active	Inactive and/or dead	Total	Dam dimensions Ht (ft)	Width (ft)	Reservoir area (acres)	Use	Applicant or owner	Remarks
La Grande Res.	Nisqually R., 16-4-33	289	1,600	1,100	2,700	212	710	45	P	City of Tacoma	
Alder Lake	Nisqually R., 15-4-9	286	180,000	52,000	232,000	330	1,600	3,065	P	City of Tacoma	

TABLE 47.—Potential storage sites in the Nisqually-Deschutes Basins

Map no.	Project name	T-R-S	River and mile	Total storage (1,000 acre-ft)	Drainage area (sq mi)	Remarks
1	Park Junction	15-7-33	Nisqually 71	--	56	
2	Ohop	16-4-19	Ohop Cr. 0.7	20	38	
3	Nisqually R. Mile 31	16-3-20	Nisqually and Deschutes	--	445	Diversion to Deschutes only
4	Nisqually R. Mile 41	16-4-32	Nisqually 41	--	292	
5	Shell Rock Ridge	15-2-2	Deschutes	48	--	Clear Lake Dike must also be constructed

Existing Reservoirs—Alder and LaGrande reservoirs on the Nisqually River are operated by the city of Tacoma for power generation. The Alder Reservoir has 232,000 acre-feet of storage and the LaGrande Reservoir has 2,700 acre-feet. Alder Reservoir is usually drawn down about 40,000 to 100,000 acre-feet during the period December through March, and is filled during May and June to accommodate power demands. These reservoirs provide only incidental flood control.

No significant regulation or storage is found on the Deschutes River. Some minor storage such as Capitol Lake is used for recreational purposes.

Detailed information on existing reservoirs in the basins is presented on Table 46.

Potential Storage Sites,—Information on potential storage sites in the basins is presented in Table 47, and shown in Figure 102.

DIVERSIONS

Nisqually River Power Plant No. 2 of the city of Tacoma is at the base of Alder Dam and about 2,800 cfs is diverted to the powerhouse and then returned to the river. Plant No. 1 is below LaGrande dam and diverts as much as 2,100 cfs for power generation. The diversion is returned to the river about one mile downstream from the dam.

The city of Centralia diverts about 720 cfs from the Nisqually River about 11 miles downstream from LaGrande dam and the water is used in a powerplant about 7 miles downstream from McKenna. The diversion bypasses about 13 miles before it is returned to the river.

In Mount Rainier National Park, about 33 cfs is diverted from Paradise River for the generation of power. The water is carried about a mile to a powerhouse and then returned to the river channel.

The city of Olympia has developed McAllister Springs, at the source of McAllister Creek in the lower Nisqually River valley, for its municipal supply. The peak demand is about 12.0 cfs and the normal daily use average about 6 cfs.

The Washington Department of Fisheries diverts 50 cfs for operation of the fishway facilities at Tumwater Falls on the Deschutes River. This water is returned to the system at the ladder entrance below the falls.

The Weyerhaeuser Timber Company diverts a maximum of 10 cfs from Big Creek near National. The water is diverted to an intermittent stream called Bowmans Creek and thence by this stream channel to a mill pond adjacent to Nisqually River. Some of the diverted water is used for domestic purposes: most is applied to mill and log-pond operations. The diversion bypasses the lower 600 feet of Big Creek and about a half mile reach of the Nisqually River.

Irrigation demands divert an estimated 5,500 acre-feet of water in the lower reaches of the Nisqually and Deschutes Rivers.

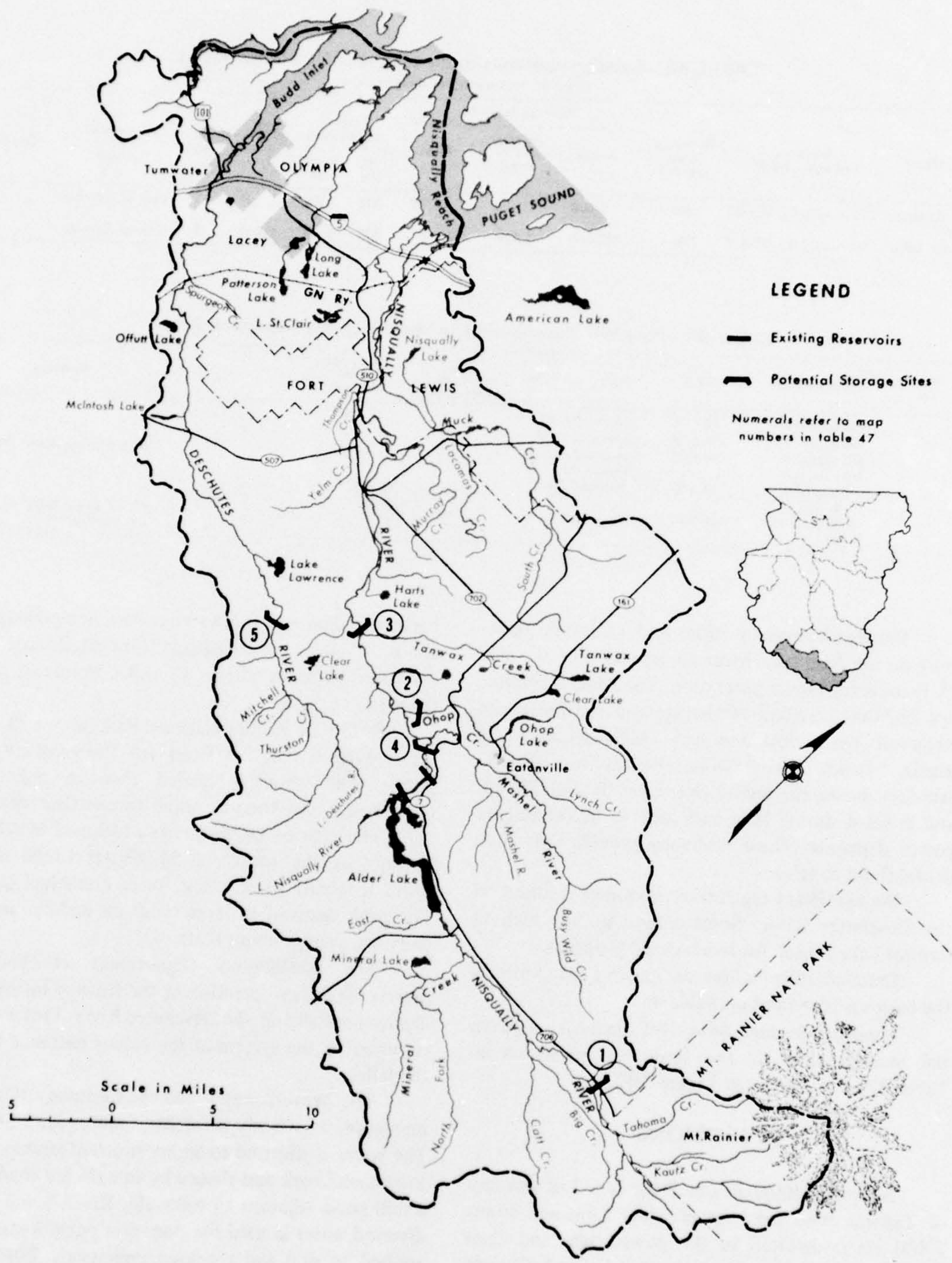


Figure 102. Existing Reservoirs and potential Storage Sites in the Nisqually—Deschutes Basins

QUALITY OF SURFACE WATER

Chemical and Sanitary Quality

Surface waters in the Nisqually-Deschutes Basins are excellent in chemical quality. The maximum dissolved-solids content reported for the Nisqually River at McKenna was 61 ppm (Table 58). For the Deschutes River near Olympia, the maximum was 89 ppm for samples collected quarterly from October 1962 to March 1966. Although the Nisqually River originates in glaciers on Mount Rainier and contains a substantial amount of glacial melt water at times, turbidity at McKenna is much lower than in other glacial streams in the Puget Sound Area. This is largely because the reservoir behind Alder Dam permits much of the suspended material to settle. The flow in the Deschutes River is derived mostly from ground-water sources, and, therefore, is usually very low in turbidity. Because of the substantial ground-water contributions, however, the stream does have a slightly higher mineral content than many major rivers in this region.

The sanitary quality of surface waters in the Nisqually-Deschutes Basins is generally good, due mostly to the low population density. Most of the samples collected from the Nisqually River at McKenna had MPN coliform values of less than 100; the maximum MPN was 2,400 (Table 58). The MPN values reported for samples collected from the Deschutes River near Olympia were in the same general range, but averaged slightly higher than the Nisqually River samples.

Stream Temperatures

In downstream order, temperature records were analyzed for the Nisqually River at National, LaGrande, and near McKenna. Records were also analyzed for Mineral Creek, a tributary to the Nisqually River, for Deschutes River near Rainier and near Olympia, and for Woodland Creek. Thermographs have been in operation at three stations (Table 59). The low temperatures of the Nisqually at National during most of the year are comparable to those of the Puyallup at Orting, and reflect the glacial origin of the Nisqually. The small variation in temperature at LaGrande is because of the stabilizing effect of Alder Lake. In contrast, larger variations in temperature occurred at National and near McKenna.

The temperature of the water in Mineral Creek is as high as 73°F in the summer. Temperatures appreciably above 70°F are characteristic of small streams that do not receive significant ground-water contribution or glacial melt water. Such streams may reach near-freezing temperatures in the winter.

Both Deschutes River and Woodland Creek are supported by ground-water contributions to the extent that they maintain winter temperatures well above freezing. The winter averages at these stations are about 43°F, although at times the temperatures have declined to the middle 30's. Both streams originate in the lowlands and are not subject to the cooling effect of water from melting glaciers or snowfields. During much of the year, the Deschutes River gains in temperature—from 1°F to 5°F—while flowing through the 16-mile reach from Rainier to Olympia.

Sediment Transports

The upper Nisqually River (above LaGrande) is formed on mountainous terrain and on flood plains of the Nisqually River. Soil types in the mountainous terrain vary considerably; on the flood plains the soils are sandy loam types and are moderately drained. Typical of the mountainous terrain elsewhere in the Puget Sound Area, excessive erosion of soils is prevented by thick vegetation cover. Stream channels in many places are cut into glacial and flood-plain deposits, which contain large quantities of cobbles and boulders. These materials slough along the banks during periods of high runoff.

The headwaters of the Nisqually River and some of its tributary streams are fed by glacial melt water. During periods of warm weather when the glaciers are melting, runoff is high and streams are turbid and sediment laden. During the winter months, flow is less and the amount of sediment transported is considerably less. The suspended sediment concentration in the Nisqually River above Alder Lake probably ranges from 1 to 60,000 ppm. Most of these sediments are deposited in Alder Lake. The Nisqually River tributaries that are not fed by glaciers generally transport little sediment.

The lower Nisqually drains alluviated flood plains and surrounding benchlands. Soils in the benchlands are sand and gravel loams, and are moderately drained to well drained. The soils on flood plains are formed from coarse-textured alluvial materials, and are well drained. Because much of the land area in the lower drainage is relatively flat, the soils are not easily eroded. Small increases in amount

of sediment released to streams have accompanied vegetation removal in areas subject to urban development, road construction, and farming.

The stream channel of the Nisqually River is cut into glacial and alluvial deposits, which are eroded and moved during periods of high runoff. Streambanks are generally protected from a large amount of erosion by a profuse cover of vegetation, but in some of the larger channel areas, landslides and bank sloughing have occurred. Sediment data obtained from the Nisqually River at McKenna during 1965 and 1966 indicate that a suspended-sediment load of 250,000 to 300,000 tons may be transported by the river during a year of normal runoff. When the mean daily discharge is about 11,500 cfs, sediment movement may total about 100,000 tons per day. The smaller streams in the lower drainage areas generally have low suspended-sediment concentrations except during periods of high runoff.

The upstream terrain in the Deschutes watershed is mountainous and contains a variety of soils with variable drainage properties. In lower parts of the basin the terrain is formed on glacial outwash plains, and most of the soils are moderately to well drained loam and sand. Numerous lakes and swamps in the lower Deschutes Basin contain poorly drained organic soils. On steeper slopes, excessive erosion is largely precluded by the vegetation. Where vegetation has been removed in areas of urban development, road construction, and farming, erosion probably has not increased much. Some of the sediments eroded in the lower Deschutes basin are deposited in numerous lakes and swamps, and therefore, do not reach the streams.

Stream channels in the upper Deschutes Basin are cut into unconsolidated fluvial and glacial materials, which are eroded and moved during periods of high streamflow. Sediment data from the Deschutes River near East Olympia in 1965 and 1966 indicate that the river may transport an average suspended sediment load of about 30,000 tons annually.

The river may transport as much as 14,000 tons per day when its mean daily discharge exceeds 5,000 cfs. Sediment concentrations in this river vary from 5 to 1,000 ppm from November through April, and are generally less than 5 ppm from May to October.

GROUND WATER

Ground-water resources in the basins are discussed separately, by lowland and mountain areas. The lowlands lie generally west and north of LaGrande, and the mountains are considered as the remaining areas to the east.

LOWLANDS

Geology and Ground Water Occurrence

The important lowland aquifers are coarse Quaternary deposits, which are rather continuous over about 570 square miles. Thicknesses of these sediments are greatest near Puget Sound, where they locally exceed 1,000 feet. The sediments become thinner and coarser to the west, south, and east, where Quaternary deposits lap onto outcrops of older consolidated rocks.

Although fresh-water aquifers may occur at depths as great as 1,000 feet, water is pumped from aquifers no deeper than about 300 feet below sea level. Ground water is generally obtained from depths less than 100 feet below land surface. For areas where Quaternary sediments are absent, ground water is obtainable only from older consolidated rocks in which well yields of 10 gpm or less can be expected.

Quaternary sediments exposed at the surface are mostly alluvium, recessional outwash, and till. Alluvium occurs mainly on the flood plain of the Nisqually River. Toward the mouth of the river, the alluvium is at least 100 feet thick and is composed mostly of sand, clay, and beds of gravel. At depths of 50 feet or more, the gravel beds serve as important artesian aquifers. Alluvium on the Deschutes flood plain is much less extensive, in both width and depth, than on the Nisqually flood plain, but it is similar in composition. Alluvial deposits are saturated to about river level.

Most of the lowland is covered with recessional outwash, particularly in Thurston County and north of Muck Creek in Pierce County. Recessional outwash is composed mostly of coarse sand and gravel, with minor amounts of clay and silt. Thickness of the recessional outwash is commonly less than 50 feet, and is greatest in areas south of Olympia, where thicknesses locally exceed 150 feet. The saturated thickness is commonly about 30 to 50 feet except in

Pierce County where it usually is much smaller and does not support large well yields.

Till, which is not an important aquifer, is exposed at the surface in most of the area south of Muck Creek, in the northwestern part of T. 18 N., R 1 E., and in the peninsulas north of Olympia. In addition, isolated outcrops of till are common in Thurston County. Till is present in the subsurface at most places. The till is generally less than 30 feet thick, but in peninsulas north of Olympia, its thickness may exceed 100 feet.

Quaternary sediments older than till are rarely exposed. Their outcrops are mainly on bluffs that border Puget Sound and the Nisqually flood plain. These older sediments contain gravel and sand aquifers at most places in the basins, and the aquifers are generally 50 to 150 feet in aggregate thickness. Most of the aquifers in these sediments are confined under artesian pressure, but locally at higher altitudes subtill deposits are partly above the water table.

Practically all recharge to aquifers in the lowlands is by infiltration of precipitation. Lowland aquifers may receive about 200,000 acre-feet of recharge in an average year. Opportunities for induced recharge from rivers do not seem favorable, owing to fineness of riverbed sediments. In those areas where permeable material underlies the surface, recharge might be feasible in the event that heavy demand should lower the water table to the extent that storage space becomes available.

Most of the ground water in the lowlands is discharged naturally into the Nisqually and Deschutes Rivers and their tributaries, and into Puget Sound through springs that occur both above and below tide-water level.

Quality of Ground Water

Water in most aquifers is generally low in dissolved solids content (less than 150 ppm), and is acceptable for practically all uses. More highly mineralized ground water is common near Puget Sound, where some fresh-water aquifers contain traces of sea water. Hardness of water in the basin is generally less than 60 ppm. Silica is usually in the 20 to 40 ppm range. Objectionable concentrations of iron occur locally, primarily in shallow aquifers that underlie the Nisqually flood plain.

The areas of poorer quality water are mainly along Puget Sound, but significant encroachment of sea water has not as yet been observed. Locally in western and southern parts of the lowlands, where Quaternary deposits are thin, many wells completed in these deposits produce highly mineralized water derived from underlying bedrock.

Utilization and Developments

Ground water pumped from wells in the lowlands is used mostly for irrigation, principally near Yelm and in the area about 5 miles southeast of Olympia. The city of Olympia pumps an average of 3,000 gpm (6 cfs) from McAllister Springs, which heads McAllister Creek. Industrial and public supply wells at Dupont and Yelm pump water at rates of about 1,200 to 1,400 gpm, and are apparently the largest yielding wells in the basin. Several large-yielding wells supply water to a brewery at Tumwater.

Wells of greatest yield in the basin pump water mostly from aquifers older than till, but substantial yields are also obtained from aquifers in rather thick and coarse post-till outwash in the irrigated area southeast of Olympia. Few wells are more than 200 feet deep, and the water-bearing zones from which they produce are commonly less than 30 feet thick. Figure 23 shows order-of-magnitude estimates of expected well yield in the basins. North of East Olympia, large well yields are often obtainable from aquifers in deposits older than till and from recessional outwash aquifers. Large yields are possible from the deeper aquifers beneath the Nisqually flood plain, particularly downstream from Nisqually. In much of the southern part of the basins and in an area southwest of Olympia, aquifers in Quaternary deposits are usually too thin to support large well yields; but elsewhere, yields of several hundred gallons per minute can be obtained from adequately developed wells. Wells that tap the deep aquifers beneath the Nisqually flood plain and the subtill aquifers in low-lying areas near Puget Sound may flow.

MOUNTAINS

In the Cascade foothills, Quaternary deposits of recessional outwash and alluvium occur over about 140 square miles. Recessional outwash, which blankets the slopes east of Ohop Valley, is dissected and drained and it does not contain extensive aquifers. Coarse alluvium occurs along the Nisqually River and some of its tributaries upstream from Alder Lake. Basic data on ground-water conditions in the alluvial deposits are lacking, but geologic evidence

suggests the presence of aquifers with sufficient permeability and saturated thickness to support large-yielding wells. Considerable recharge to the aquifers is inferred from the abundance of precipitation.

Elsewhere in the mountains, ground water is obtainable only from consolidated and semiconsolidated rocks in which well yields of 10 gpm or less can be expected.

WEST SOUND BASINS

SURFACE WATER

The West Sound Basins occupies an area of 2,620 square miles, including 2,022 square miles of land and inland water. A map of the Basins is shown on Figure 114. The Basins are bounded on the east by the main channel of Puget Sound and on the west by the Olympic Mountains. Hood Canal extends 68 miles along the foothills of the Olympic Mountains with a fairly uniform width of 1½ to 2 miles and separates the study area into two distinct areas, the Olympic and Kitsap Peninsulas. In addition, the study area contains numerous islands, channels, inlets, passages, and bays of lower Puget Sound. The largest islands are Vashon, Bainbridge, Maury, Fox, McNeil, Anderson and Harstene.

Because of the striking differences in climate and topography between the Olympic and Kitsap Peninsulas, the streams on the Olympic Peninsula are comparatively large and swift whereas those draining the Kitsap Peninsula and its associated islands are rather small. Principal rivers draining the east slope of the Olympic Peninsula, the Skokomish, Hamma Hamma, Duckabush, Dosewallips, Big Quilcene, and Little Quilcene, flow into Hood Canal (actually, Big Quilcene and Little Quilcene Rivers flow into Quilcene Bay, an arm of Hood Canal). All of these rivers head in the extremely rugged forested areas of the Olympic National Park and Olympic National Forest. Only the Skokomish River passes through a broad flood plain before emptying into Hood Canal.

Because of its highly irregular configuration, the Kitsap Peninsula is drained by hundreds of small streams. Only 12 streams drain more than 10 square miles of surface area, and most of the others drain less than 1 square mile. Due to the smallness of these drainages and their location in the rain shadow of the Olympic Mountains, streamflows are small in comparison to those on the Olympic Peninsula. All streams on the Kitsap Peninsula originate in the bedrock area of Green Mountain or Gold Mountain or the glacial outwash plains that are characteristic of the Puget Sound lowlands.

STREAMFLOW

Runoff Characteristics

In the exteme headwater areas of certain east Olympic slope streams, mean annual runoff exceeds 160 inches. Runoff decreases rapidly to the east and north, however, as the Olympic Mountains rain shadow intensifies. The lowest production occurs in the vicinity of Port Townsend and the northern extremity of the Kitsap Peninsula. There, runoff is estimated to average less than 10 inches annually. Throughout the lowland areas of the Kitsap Peninsula, annual runoff averages about 25 inches. Mean annual runoff for the entire 2,022-square-mile area of land and inland water in the study area is estimated to be about 46 inches, or 4.9 million acre-feet.

Records obtained at four gaging sites were selected to represent conditions in major water-producing streams along the eastern slopes of the Olympic Mountains. For the Dosewallips River near Brinnon, the mean annual runoff, adjusted to the period 1931-60, was 475 cfs. This is equivalent to 344,000 acre-feet per year. On a unit-runoff basis, this drainage has averaged 5.1 cfs per square mile. Adjusted to the same period, the mean annual runoff of the Duckabush River near Brinnon is 407 cfs or 295,000 acre-feet. The corresponding unit-runoff quantity is 6.1 cfs per square mile. Similarly, mean annual runoff from the Hamma Hamma watershed above the stream gage averaged 337 cfs or 244,000 acre-feet (6.6 cfs per square mile). Near Union, the mean annual runoff for the South Fork Skokomish River averaged 708 cfs, or 513,000 acre-feet, and 9.3 cfs per square mile. In general, the drainages above these four gages have similar relief and altitude, but a sizable difference in unit-runoff production is evident between the northern and southern basins along these Olympic Mountain slopes. This difference reflects an intensification of the Olympic rain shadow in a northeasterly direction in this part of the Puget Sound Area.

The contrasting character of runoff from the lowland parts of the West Sound Basins is shown by the record for Goldsborough Creek near Shelton. The adjusted mean annual discharge for the period 1931-60 at this gage was 109 cfs, or 79,000 acre-feet. On a square-mile basis, runoff from this watershed amounts to only 2.8 cfs. Similar conditions, with even less production, prevail throughout the Kitsap peninsula area.

Average annual discharges of selected streams in the Basins are depicted in Figures 103 and 104. The lowest average flow of record on the South Fork

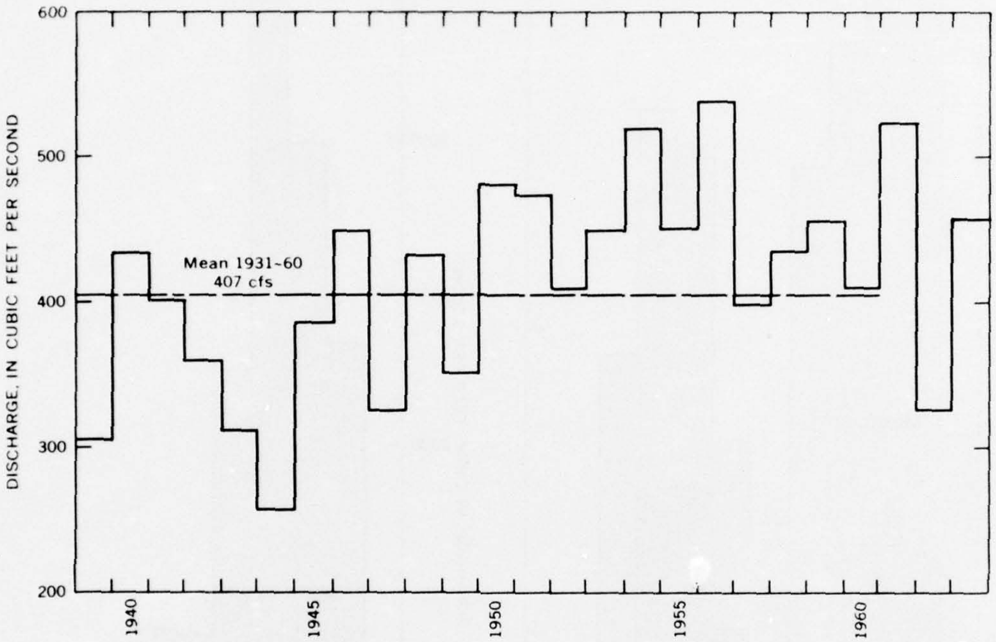


FIGURE 103.—Annual discharges, Duckabush River near Brinnon.

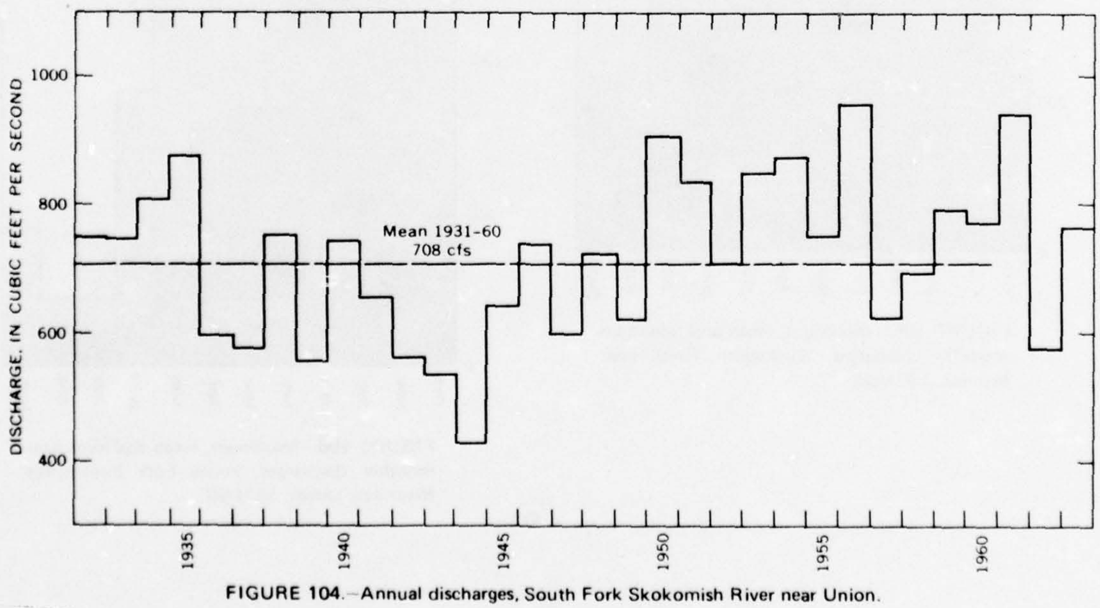


FIGURE 104.—Annual discharges, South Fork Skokomish River near Union.

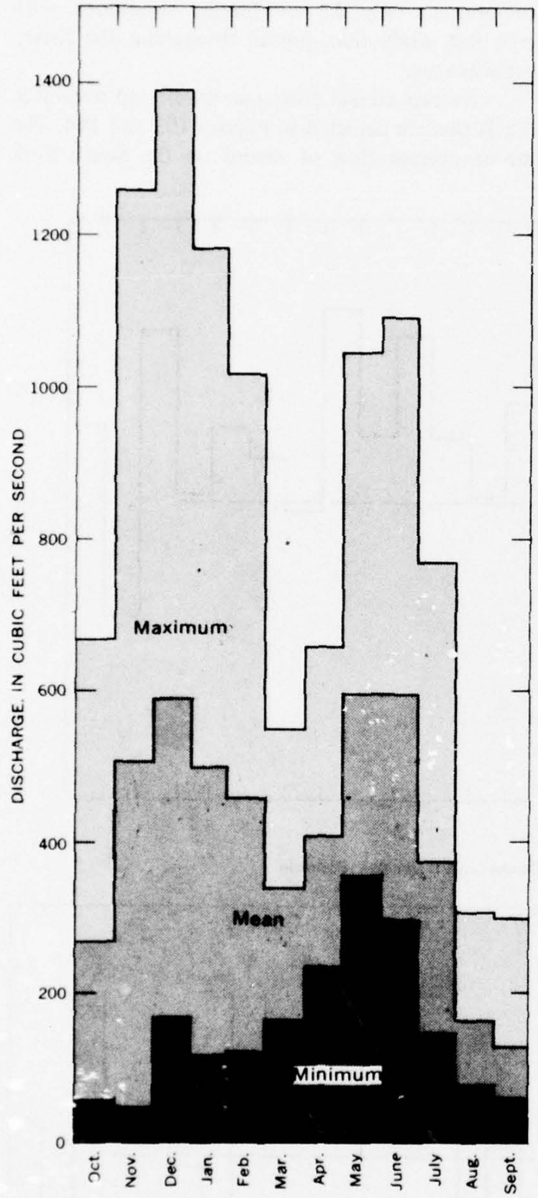


FIGURE 105.—Maximum, mean and minimum monthly discharges, Duckabush River near Brinnon, 1931-60.

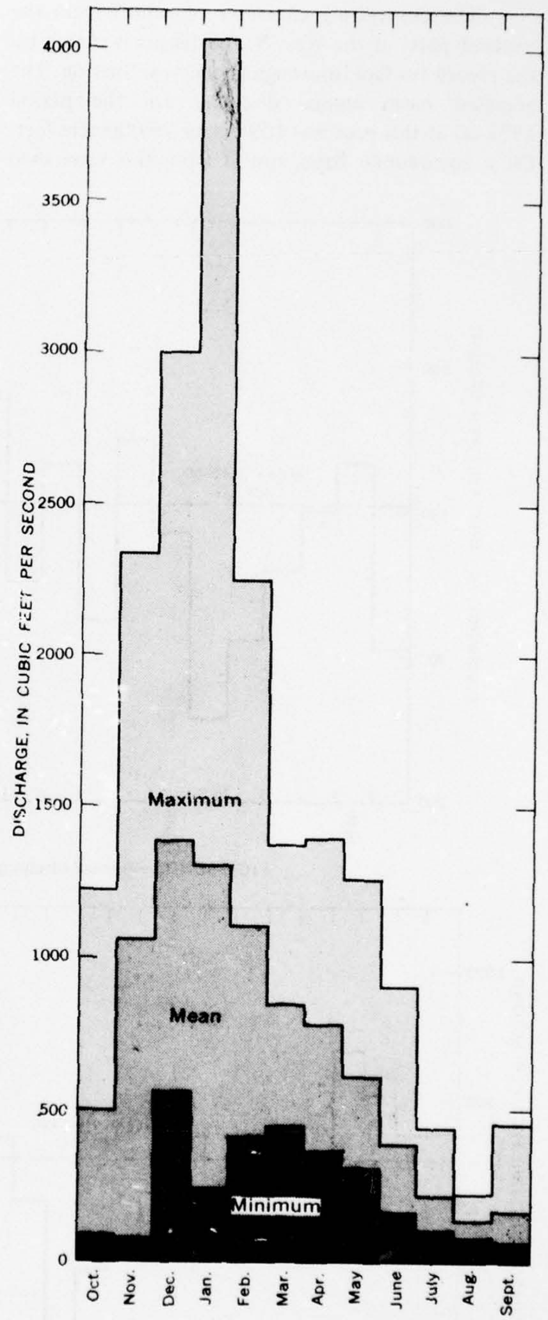


FIGURE 106.—Maximum, mean and minimum monthly discharges, South Fork Skokomish River near Union, 1931-60.

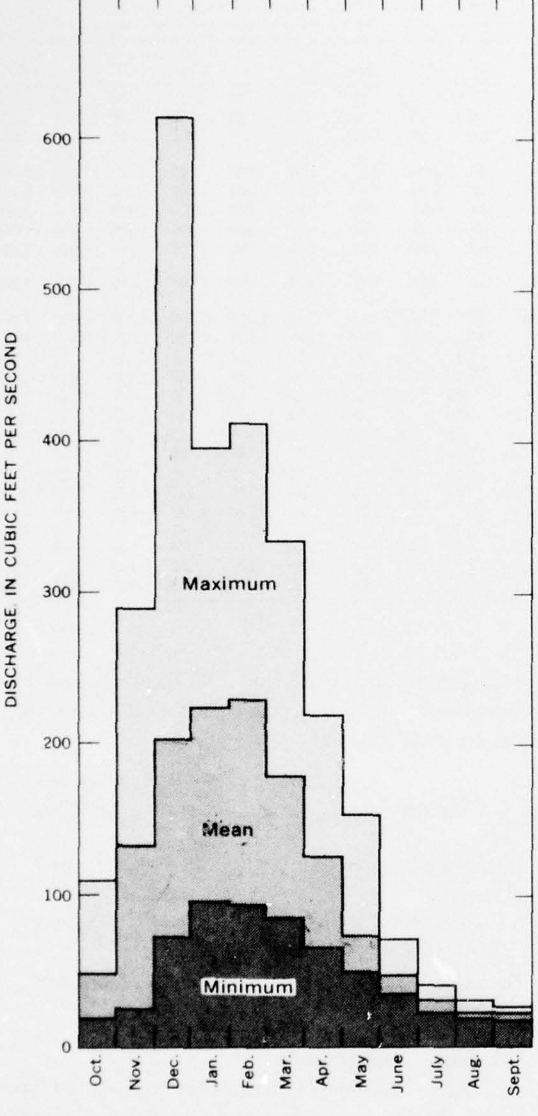


FIGURE 107.—Maximum, mean and minimum monthly discharges, Goldsborough Creek near Shelton, 1931-60.

Skokomish River was 426 cfs in water year 1944; this represented 60% of the 1931-60 mean. The highest recorded average flow, 957 cfs, occurred in 1956. This flow is approximately 135% of the long-term mean.

Mean monthly discharges at selected gaging stations are shown as bar charts in Figures 105-107. The streams show two distinctly different flow regimens. Those streams lying most directly in the lee of the Olympic Mountains exhibit two peak flow periods; one from winter precipitation and the other from snowmelt and spring rains. A comparison shows that the spring runoff peak is more prominent in those watersheds that lie most directly in the Olympic Mountains rain shadow. To the south, where the rain shadow disappears, the winter peak becomes dominant and the two seasonal peaks tend to merge into one long period of high flows. With the exception of the Dosewallips River, the maximum recorded monthly flows occurred during the months of December and January.

Minimum monthly flows generally occur during August and September. In the northern part of the study area, however, the period of minimum flow tends to extend into the month of October.

Hydrograph characteristics for the West Sound Basins were determined for Dewatto, South Fork Skokomish, and Duckabush Rivers.

The stream gage on Dewatto River near Dewatto measures runoff from 84% of the basin, on the western side of the Kitsap Peninsula. Streamflow usually begins to increase in September, following the summer period of base flow. The hydrograph from October to April is characterized by a series of sharp peaks superimposed on a base flow, which is highest in February. Runoff decreases from March to July as a result of reduced precipitation, and the minimum base flow is usually reached by the first part of July.

The stream gage on South Fork Skokomish River near Union measures runoff from 73% of that basin. Streamflow usually begins to increase in September from the summer base flow of about 125 cfs. During October-April the discharge is characterized by a series of sharp peaks superimposed upon a base flow which peaks in December. Runoff generally decreases from January to March as a result of reduced rainfall. As temperatures begin rising, the discharge is maintained by snowmelt, and averages about 800 cfs during March and April. Streamflow then recedes to minimum values as the snowpacks are depleted, usually by August.

The Duckabush River gage near Brinnon measures runoff from 87% of that basin. Streamflow during the period October through March is characterized by a series of sharp rises superimposed upon a base flow which is highest in December. Runoff generally decreases from January to the middle of March as a result of reduced precipitation. As temperatures begin to rise in March, snowmelt causes

TABLE 48.—Flow-duration data for streams in the West Sound Basins

Gaging station	Period of analysis	Flow, in cubic feet per second, which was equaled or exceeded for indicated percent of time											
		99	95	90	80	70	50	30	20	10	5	1	0.1
Snow Creek near Maynard	1953-61	1.8	2.3	2.8	3.9	5.7	11.5	19	26	39	54	105	260
Chimacum Creek near Chimacum	1953-57	2.6	3.2	3.6	4.3	5.1	8.3	14.5	20	32	50	121	210
Little Quilcene near Quilcene	1927, 1952-57	7.5	11	15.5	22	29	42	60	75	104	138	250	480
Dosewallips River near Brinnon	1931-49	90	119	142	185	230	350	520	640	860	1,100	1,750	3,500
Duckabush River near Brinnon	*1939-65*	*56*	*77*	*100*	*150*	*200*	*310*	*460*	*580*	*790*	*1,050*	*2,070*	*3,900*
Hamma Hamma River near Eldon	1952-64	51	69	90	138	185	290	420	515	700	930	1,700	3,200
Jefferson Creek near Eldon	1958-64	12	16	20	35	56	94	156	220	340	500	930	1,650
North Fork Skokomish River below Staircase Rapids near Hoodsport	1925-65	42	65	89	150	220	360	550	700	1,000	1,350	2,500	5,000
South Fork Skokomish River near Potlatch	1924-32, 1947-64	58	79	98	145	220	395	640	870	1,300	1,850	3,500	6,800
South Fork Skokomish River near Union	1932-65	75	90	108	158	250	450	740	1,000	1,550	2,300	4,600	9,200
Skokomish River near Potlatch	1944-61	150	180	208	280	410	760	1,240	1,700	2,750	3,950	7,400	16,000
Union River near Bremerton	1946-59	.47	.64	.82	1.3	2.2	6.7	11.5	17	30	45	96	225
Union River near Belfair	1948-59	16	18	19.5	22.5	25.5	34	50	69	110	160	335	700
Mission Creek near Bremerton	1946-53	0	0	0	.06	.38	2.6	6.9	11.0	19.5	29	46	100
Mission Creek near Belfair	1946-52	17	.28	.37	.50	.67	3.1	13	20	36	53	94	235
Gold Creek near Bremerton	1946-61	.41	.54	.65	.88	1.2	3.1	6.4	9.2	15	22	46	94
Tahuya River near Bremerton	1946-56	.22	.35	.60	1.2	2.2	7.5	11	35	63	95	180	350
Panther Creek near Bremerton	1946-53	0	0	0	.05	.10	.60	2.9	5.1	10	14	23.5	37
Tahuya River near Belfair	1946-56	0	.07	.16	.41	1.5	13	46	78	140	210	410	800
Dewatto River near Dewatto	1948-54, 1959-64	11.5	13.5	14.5	17	21	37	67	96	167	250	450	930
Huge Creek near Wauna	1948-64	3.9	4.2	4.5	5.0	5.6	7.3	10.5	14	24	36	68	150
Goldsborough Creek near Shelton	1952-64	18	21	24	29	37	75	130	178	280	380	590	1,000
Skookum Creek at Kamilche	1952-58	1.7	2.1	2.4	3.4	6.0	25	60	90	145	205	370	700

increasing streamflows that reach a peak usually by June. Following the snowmelt peak streamflow recedes to minimum base flow usually by September. The variability of the daily flow of streams in the West Sound Basins is presented as flow-duration data for selected gaging stations in Table 48.

Flood Characteristics

Floods caused by abundant rainfall and accompanying snowmelt produce characteristically sharp rises on a hydrograph, followed by recessions almost as rapid. Two or more peaks often occur within a 1-to2-week period.

The maximum instantaneous discharge of record for the three stream-gaging sites investigated in the West Sound Basins are as follows: Dewatto River near Dewatto, 2,160 cfs on January 15, 1961; South Fork Skokomish River near Union, 21,600 cfs on January 22, 1935; and Duckabush River near Brinnon, 8,960 cfs on November 26, 1949.

Flood-frequency curves for streams in the West Sound Basins include those for Dewatto River near Dewatto, South Fork Skokomish River near Union, and Duckabush River near Brinnon. The frequency curves are presented in Figures 108-110. Frequency statistics were extended for these stations to longer equivalent periods by correlation with data for the North Fork Skokomish River below Staircase Rapids near Hoodsport, which has a 40-year record. The periods of record and equivalent record for each station are as follows:

Station	Period of Record	Equivalent Record
Dewatto River near Dewatto	1948-54, 1959-64	16 years
S.F. Skokomish River near Union	1932-64	37 years
Duckabush River near Brinnon	1939-64	35 years

Low-Flow Characteristics

Low-flow characteristics of streams in the West Sound Basins were compared using indexes from low-flow frequency curves at 22 gaging stations (Table 49). The low-flow indexes are good in streams draining the east slope of the Olympic Mountains and are fair in most of the remainder of the study area. (Fig. 22). Small areas of poor indexes are in the southern part of the Kitsap Peninsula and in the extreme southwestern part of the basins. The streams in the basins have fairly wide differences in the slope and spacing indexes which show the variability of low flow. In general the low flows of the Olympic Peninsula streams vary more from year to year than those in the other areas. In the southern Kitsap

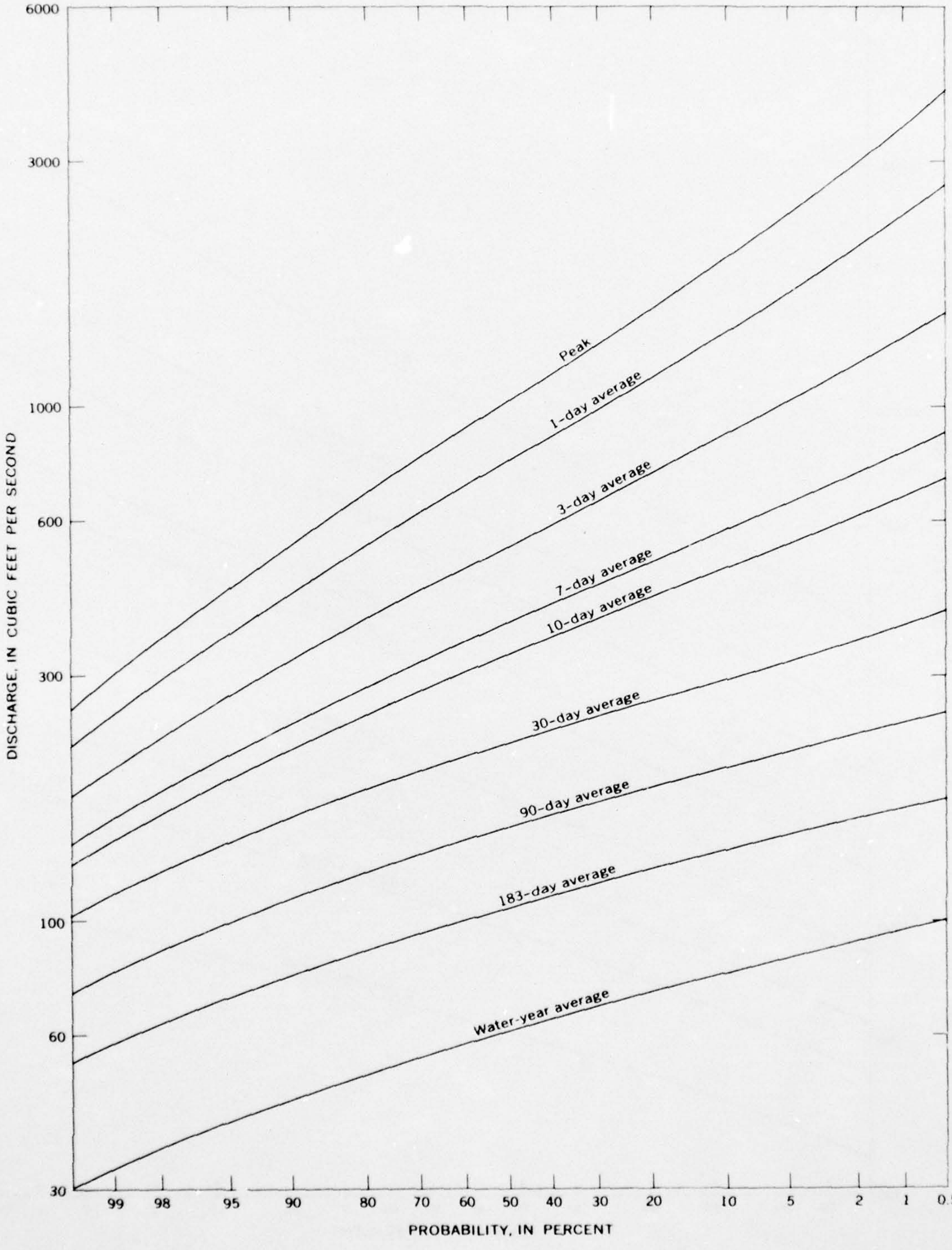


FIGURE 108.–Probability curves of annual maximum flows for specified time periods, Dewatto River near Dewatto.

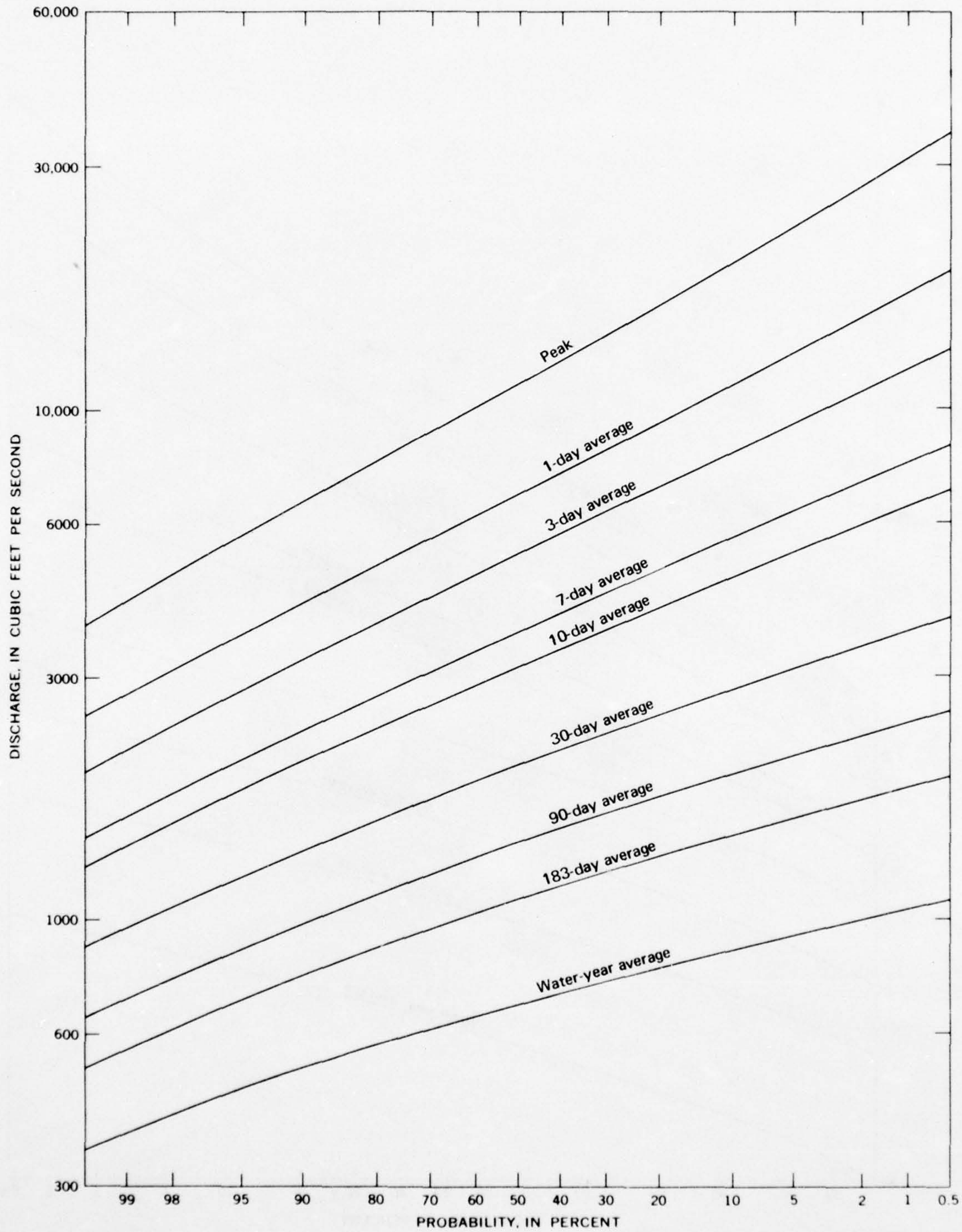


FIGURE 109.—Probability curves of annual maximum flows for specified time periods, South Fork Skokomish River near Union.

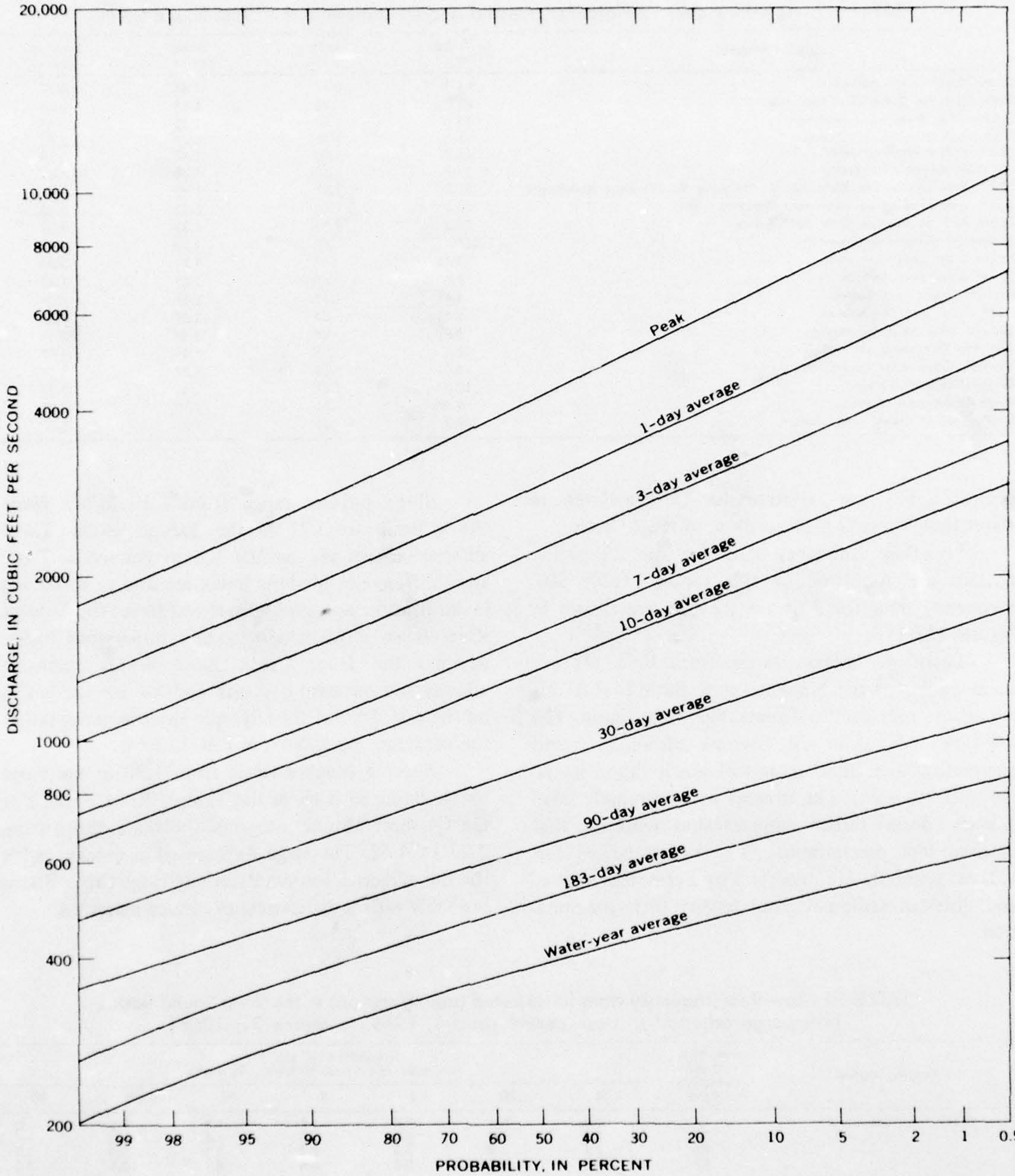


FIGURE 110.--Probability curves of annual maximum flows for specified time periods, Duckabush River near Brinnon.

TABLE 49.—Low-flow characteristics for selected gaging stations in the West Sound Basins

Gaging station	Drainage area	Low-flow index	Slope index	Spacing index
Snow Creek near Maynard	11.2	0.17	1.58	3.47
Little Quilcene River near Quilcene	23.7	.46	1.67	2.27
Dosewallips River near Brinnon	93.5	1.41	1.32	2.65
Duckabush River near Brinnon	66.5	1.17	1.47	3.85
Hamma Hamma River near Eldon	51.3	1.15	1.47	3.73
Jefferson Creek near Eldon	21.6	.60	1.46	4.62
North Fork Skokomish River below Staircase Rapids near Hoodsport	57.2	1.31	1.39	4.46
South Fork Skokomish River near Potlatch	63.4	1.40	1.35	3.15
South Fork Skokomish River near Union	76.3	1.23	1.30	3.28
Skokomish River near Potlatch	227	.78	1.24	2.70
Union River near Bremerton	3.16	.19	1.71	3.00
Union River near Belfair	19.8	.87	1.29	1.42
Mission Creek near Belfair	4.43	.05	2.56	4.26
Gold Creek near Bremerton	1.51	.34	1.59	2.55
Tahuya River near Bremerton	5.99	.06	3.67	8.18
Dewatto River near Dewatto	18.4	.65	1.21	1.83
Dogfish Creek near Poulsbo	5.01	.56	1.22	1.61
Burley Creek at Burley	10.7	1.27	1.31	1.34
Huge Creek near Wauna	6.47	.66	1.19	1.30
Goldsborough Creek near Shelton	39.3	.51	1.32	2.00

Peninsula, low-flow variations for Tahuya River are about three times as great as those of Huge Creek.

Low-flow frequency data for the 22 gaging stations are tabulated in this report (Table 50). Frequency data for 3 of the 22 sites are shown in Figures 111-113.

Low-flow indexes range from 0.05 cfs per square mile for the Mission Creek Basin to 1.41 cfs per square mile for the Dosewallips River Basin. The low-flow indexes in the Olympic Mountain basins may reflect the large amount of precipitation in the high-altitude areas. The streams with extremely small indexes drain rather impermeable material that receives less precipitation. The basins having fair indexes generally are underlain by permeable alluvial and outwash sediments, but receive little precipitation.

Slope indexes range from 1.19 in the Huge Creek Basin to 3.71 in the Tahuya Basin. These adjacent basins are on the Kitsap Peninsula. Their large differences in slope index are due to variations in infiltration and ground-water storage; the Tahuya River Basin is formed on rather impervious rocks, whereas the Huge Creek Basin drains extensive alluvial and outwash deposits. Indexes for the basins on the east slope of the Olympic Mountains are rather uniform, ranging only from 1.30 to 1.67.

Spacing indexes range from 1.30 in the Huge Creek Basin to 8.18 in the Tahuya River Basin. For the Olympic Mountain basins, the values range from 2.27 to 4.62. The large differences in spacing index for the adjacent Tahuya River and Huge Creek Basins probably reflect differences in surface materials.

TABLE 50.—Low-flow frequency data for selected gaging stations in the West Sound Basins
[Discharge adjusted to base period April 1, 1946, to March 31, 1964]

Gaging station	Number of consecutive days	Streamflow in cfs, for indicated recurrence intervals, in years						
		1.05	1.30	2.0	5	10	20	30
Snow Creek near Maynard	7	4.0	2.6	1.9	1.5	1.3	1.2	1.2
	30	5.0	3.2	2.4	1.8	1.6	1.5	1.4
	90	7.7	4.9	3.5	2.5	2.1	1.8	1.7
	183	16.4	9.4	6.6	4.8	4.1	3.6	3.3
Little Quilcene River near Quilcene	7	22	15	11	8.4	7.3	6.6	6.3
	30	25	17	13	9.6	8.4	7.5	7.0
	90	28	18	14	11	9.9	9.3	9.0
	183	50	33	25	19	18	17	16
Dosewallips River near Brinnon	7	178	150	132	114	106	100	96
	30	215	178	154	132	123	118	114
	90	360	270	222	184	170	160	156
	183	490	405	350	300	280	268	260
Duckabush River near Brinnon	7	111	93	78	64	58	53	51
	30	146	117	97	79	70	64	61
	90	325	212	160	120	108	100	96
	183	500	365	300	245	224	212	209

TABLE 50.—Continued

Gaging station	Number of consecutive days	Streamflow in cfs, for indicated recurrence intervals, in years						
		1.05	1.30	2.0	5	10	20	30
Hamma Hamma River near Eldon	7	101	74	59	47	43	40	39
	30	121	87	69	55	50	46	45
	90	245	153	113	85	76	70	68
	183	308	260	220	188	177	170	168
Jefferson Creek near Eldon	7	22	16	13	10.6	9.6	8.9	8.6
	30	28	20	16	12.7	11.5	10.8	10.3
	90	59	38	28	20.5	18	16	15
	183	102	75	60	50	46	44	43
North Fork Skokomish River below Staircase Rapids near Hoodsport	7	124	92	75	62	56	54	52
	30	164	118	94	74	67	62	60
	90	340	215	160	120	107	98	95
	183	580	420	335	270	252	240	235
South Fork Skokomish River near Potlatch	7	129	103	89	76	70	66	64
	30	145	116	99	83	77	73	71
	90	230	172	140	110	98	90	86
	183	480	352	280	230	210	200	190
South Fork Skokomish River near Union	7	142	111	94	80	75	72	70
	30	157	124	105	88	82	77	74
	90	260	192	153	121	108	99	94
	183	520	380	308	250	226	210	204
Skokomish River near Potlatch	7	220	197	178	160	151	144	140
	30	260	220	200	176	168	160	158
	90	350	290	250	218	205	197	190
	183	810	590	480	380	350	325	315
Union River near Bremerton	7	0.9	0.7	0.6	0.46	0.40	0.35	0.32
	30	1.1	.8	.65	.50	.43	.38	.35
	90	1.5	1.0	.8	.7	.55	.50	.48
	183	3.1	2.3	1.8	1.4	1.2	1.1	1.0
Union River near Belfair	7	22.8	19.5	17.2	15	14	13.3	13
	30	25	21.2	18.8	16	15	14	13.7
	90	26	22.2	20	17.6	16.5	15.8	15.5
	183	31	27	24.4	21.2	20	19	18
Mission Creek near Belfair	7	.43	.32	.23	.15	.11	.09	.08
	30	.53	.39	.28	.18	.14	.11	.10
	90	.63	.46	.36	.25	.20	.16	.15
	183	2.2	1.4	.98	.66	.52	.43	.39
Gold Creek near Bremerton	7	.80	.62	.51	.40	.36	.32	.30
	30	.92	.70	.57	.45	.40	.36	.34
	90	1.1	.86	.71	.56	.49	.43	.40
	183	2.1	1.6	1.3	1.0	.88	.78	.73
Tahuya River near Bremerton	7	1.0	.55	.33	.17	.12	.09	.08
	30	1.4	.73	.42	.22	.16	.12	.10
	90	2.1	1.2	.73	.40	.29	.22	.18
	183	7.0	4.1	2.7	1.7	1.3	1.0	.90
Dewatto River near Dewatto	7	16	13.5	12	10.9	10.2	9.9	9.7
	30	18	15.2	13.7	12.2	11.8	11.4	11.2
	90	19.5	17	15.2	13.9	13.2	13	12.7
	183	28	24	22	19	18	16.8	16
Dogfish River near Poulsbo	7	3.7	3.1	2.8	2.6	2.4	2.3	2.2
	30	4.1	3.4	3.1	2.8	2.6	2.5	2.4
	90	4.5	3.9	3.4	3.1	2.9	2.8	2.7
	183	5.4	4.8	4.5	4.0	3.8	3.6	3.5
Burley Creek at Burley	7	16.7	15	13.6	12	11.1	10.4	10
	30	18.2	16	14.7	13	12.3	11.9	11.6
	90	20.2	17.4	15.7	14	13.4	13	12.6
	183	25	21	18.2	16	15	14.4	14
Huge Creek near Wauna	7	5.2	4.6	4.3	3.9	3.7	3.6	3.5
	30	5.6	4.9	4.6	4.1	4.0	3.9	3.8
	90	6.1	5.3	4.8	4.4	4.2	4.1	4.0
	183	7.2	6.2	5.6	4.9	4.7	4.5	4.4
Goldsborough Creek near Shelton	7	25	22.5	20	17.3	16	15.2	14.9
	30	27.5	24.5	22	19	17.8	16.8	16
	90	31	27.5	25	21.2	19.5	18	17.2
	183	52	45	40	33	29	21	19.5
Skookum Creek near Kamilche	7	3.2	2.5	2.1	1.7	1.6	1.5	1.5
	30	3.9	3.0	2.5	2.2	2.1	2.0	2.0
	90	5.3	3.7	3.0	2.4	2.2	2.1	2.1
	183	15.5	11.3	8.6	5.7	4.4	3.4	2.9
Kennedy Creek near Kamilche	7	3.6	3.1	2.8	2.3	2.1	1.9	1.8
	30	4.2	3.6	3.1	2.6	2.3	2.1	2.0
	90	5.6	4.4	3.7	3.0	2.8	2.6	2.5
	183	16	12	9.1	6.4	5.1	4.2	3.7

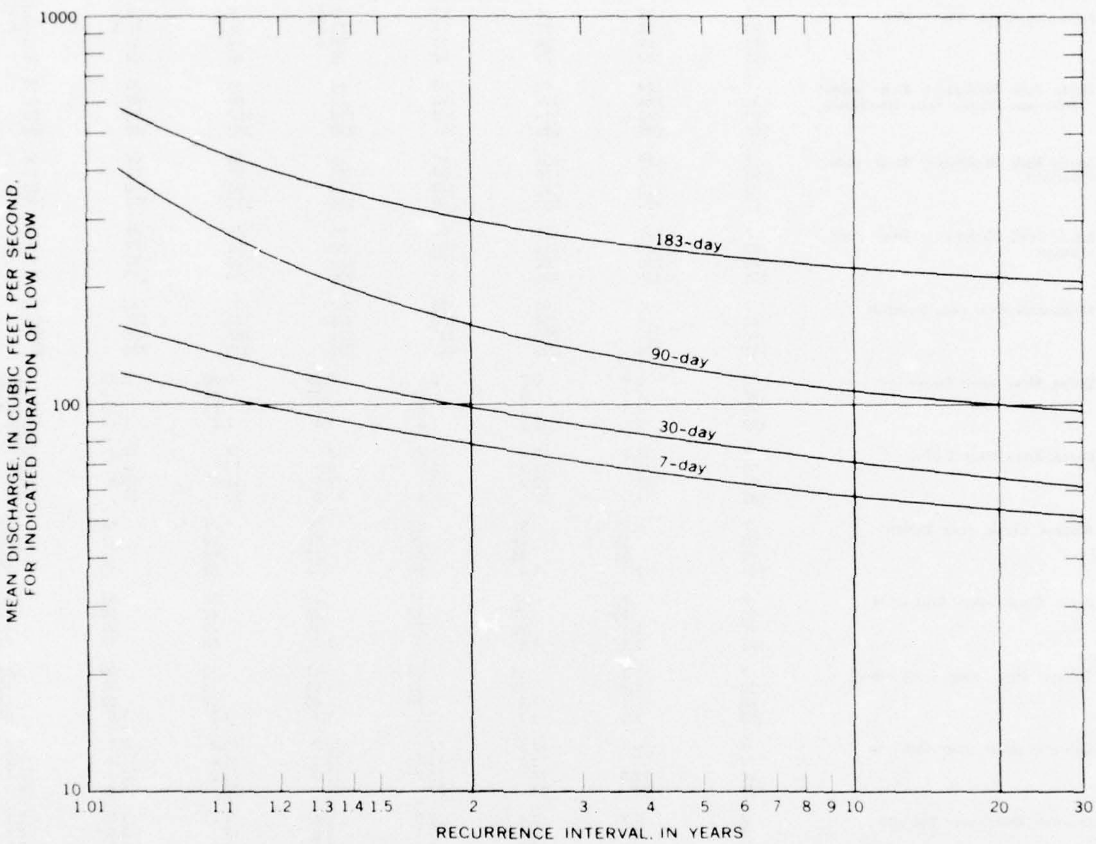


FIGURE 111.—Low-flow frequency, Duckabush River near Brinnon, 1946-63.

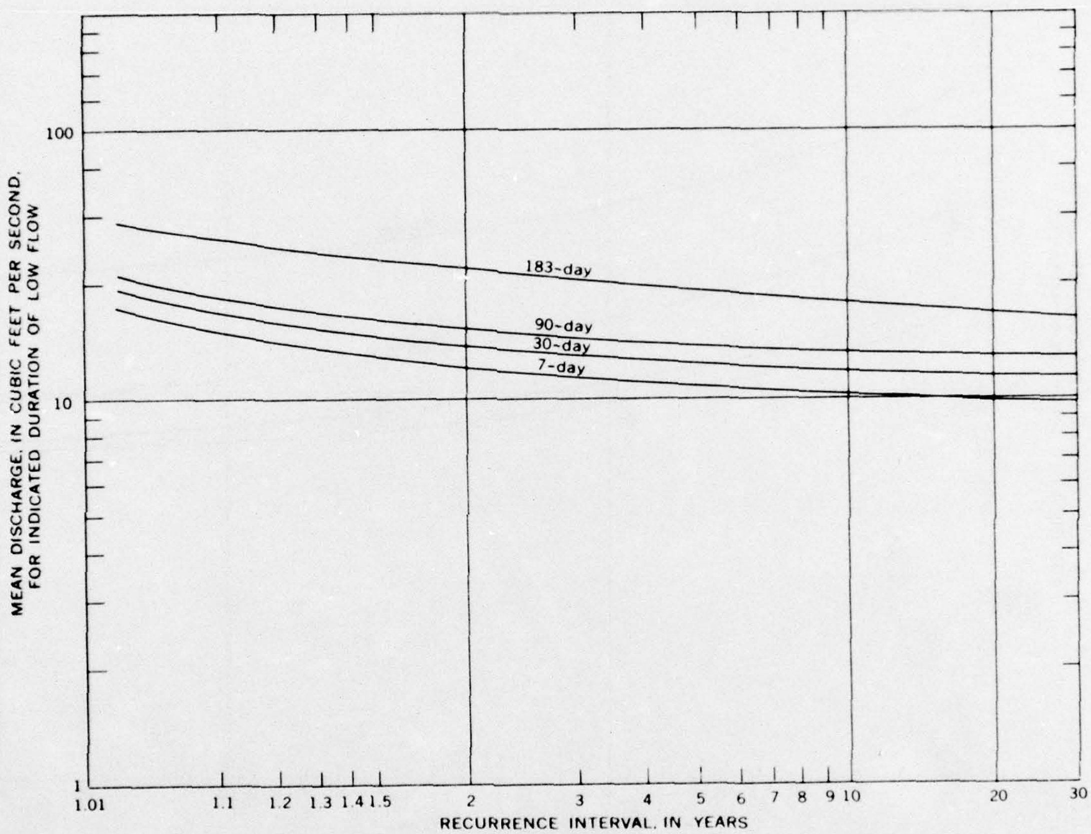


FIGURE 112.—Low-flow frequency, Dewatto River near Dewatto, 1946-63.

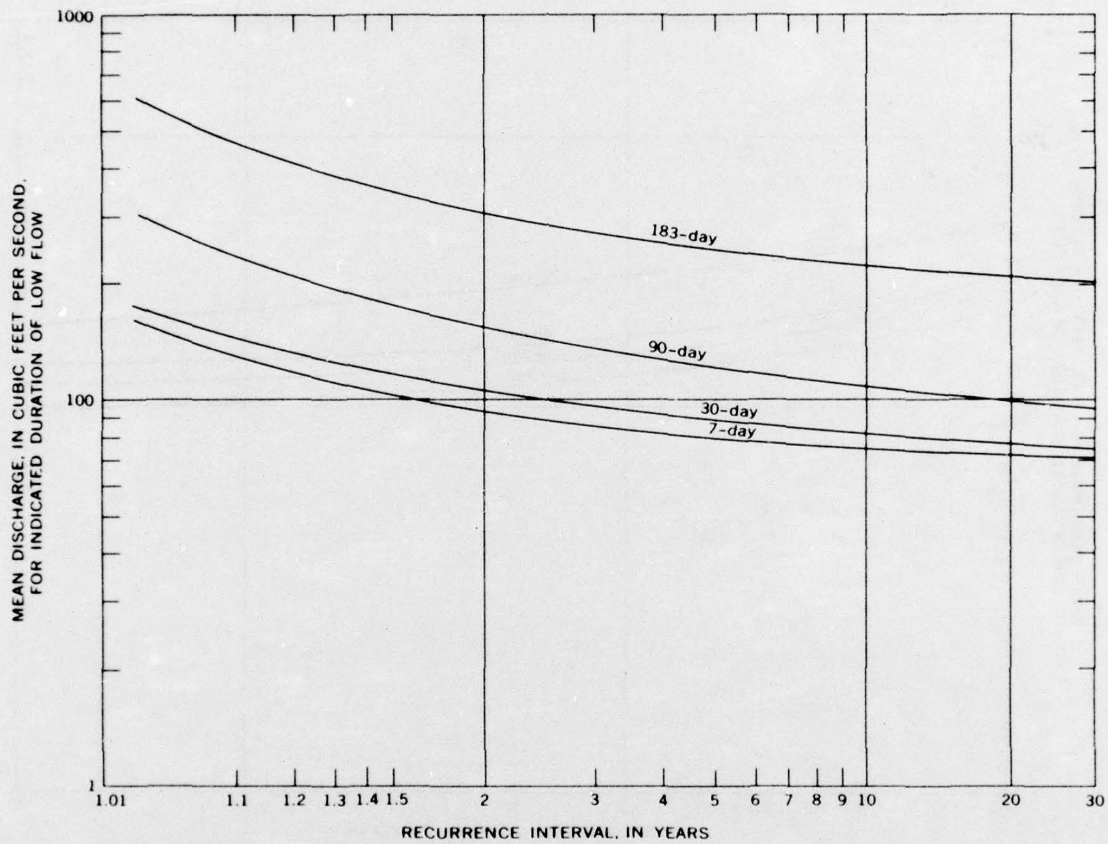


FIGURE 113.—Low-flow frequency, South Fork Skokomish River near Union, 1946-63.

STORAGE AND REGULATION

Natural Surface Storage

The total amount of storage in lakes and glaciers in the basins is not known, but the surface area covered by these water bodies provides at least a comparative indication of the amount of water that is stored. The total lake surface area is 18.8 square miles, of which 6.7 square miles consists of reservoirs. The only glaciers in the basins, located in the upper watershed of the Dosewallips River, total 0.7 square mile or less in area, and have little effect on streamflow.

Reservoirs

The following discussion of existing and potential reservoirs in the West Sound Basins is restricted mainly to those with a capacity of 5,000 acre-feet or more. Smaller reservoirs are tabulated only because of their importance as sources of water for local communities. Existing reservoirs and potential storage sites in the basins are shown in Figure 114.

Existing Reservoirs—Flow has been regulated for the generation of power on the North Fork Skokomish River by Lake Cushman since 1925. The entire runoff of the North Fork basin is normally stored in Cushman No. 1 reservoir and is diverted from Cushman No. 2 reservoir into Hood Canal through the city of Tacoma's power plant near Potlatch. The Cushman Project presently has over 460,000 acre-feet of total storage and 360,000 acre-feet of active storage. The power diversions generally preclude an appreciable discharge in the North Fork Skokomish River below Cushman No. 2 Dam.

Table 51 presents detailed information on the existing reservoir storage. Several small municipal storage reservoirs for Bremerton and Port Townsend are also located in the study area. There is no regulation or storage on Goldsborough Creek, South Fork Skokomish River, Hamma Hamma River, Duckabush River, Quilcene River, or Dosewallips River.

Potential Storage Sites—Information on potential storage sites is listed in Table 52 and site locations are shown in Figure 114. Potential sites on the Kitsap Peninsula are discussed in detail by Garling and Molenaar (1965 pg. 147).

DIVERSIONS

The Union River, one of the largest streams on the Kitsap Peninsula, is used as the city of Bremerton's main source of municipal water. The city diverts approximately 10 cfs from this stream and also uses water from Charlestown, Anderson and Gorst Creeks and Lake Alexander. The Union River and Anderson Creek developments presently serve as the primary active sources of supply, while Gorst Creek is retained in the system mainly for use on a standby basis and the Charleston Creek facilities have essentially been abondoned.

In conjunction with the industrial operations of Simpson Logging Company, Rainier Pulp and Paper Company, and Rayonier, Inc. in Shelton, about 23 cfs is diverted from Goldsborough Creek. About 4 cfs is also diverted from Coffee Creek at a point near its mouth. All the diversion is discharged to tidewater.

Tacoma is permitted to divert 1,000 cfs at Cushman No. 1 Dam on the North Fork Skokomish River for power generation. The flow is returned directly to the North Fork channel after passing through the powerplant. From a second dam, about 2.5 miles downstream, the city is also permitted to divert 1,000 cfs. The water is transported 2.8 miles to Cushman Power Plant No. 2 on Hood Canal and discharged directly to tidewater. In normal operation, water is seldom spilled to the North Fork channel below the lower Lake Cushman Dam.

A small private hydroelectric powerplant uses about 5 cfs diverted from Lilliwaup Creek. All the water is returned to the creek just below Lilliwaup Falls.

The city of Port Townsend diverts water from Little Quilcene and Big Quilcene Rivers. The city requested diversions of 30 cfs from each stream but the diversions from Little Quilcene River has been limited to 9.56 cfs. The average demand by the city and its industries is about 21 cfs. The combined system, however, has sufficient capacity to deliver water at the rate of about 31 cfs during periods of peak demand.

The Bureau of Sport Fisheries and Wildlife operates a salmon and trout hatchery 2 miles south of Quilcene and is permitted to divert a total of 40 cfs from the Big Quilcene River and one of its tributaries, Penny Creek. The diverted water is returned to the river about 550 feet downstream from the Big Quilcene River point of diversion.

The Washington Department of Fisheries Skokomish River Salmon Hatchery, located on Purdy Creek, diverts 10 cfs from Purdy Creek which is returned below the hatchery ponds. The Hood Canal Salmon Hatchery at Hoodsport diverts 17.4 cfs from Finch Creek which is returned below the hatchery ponds.

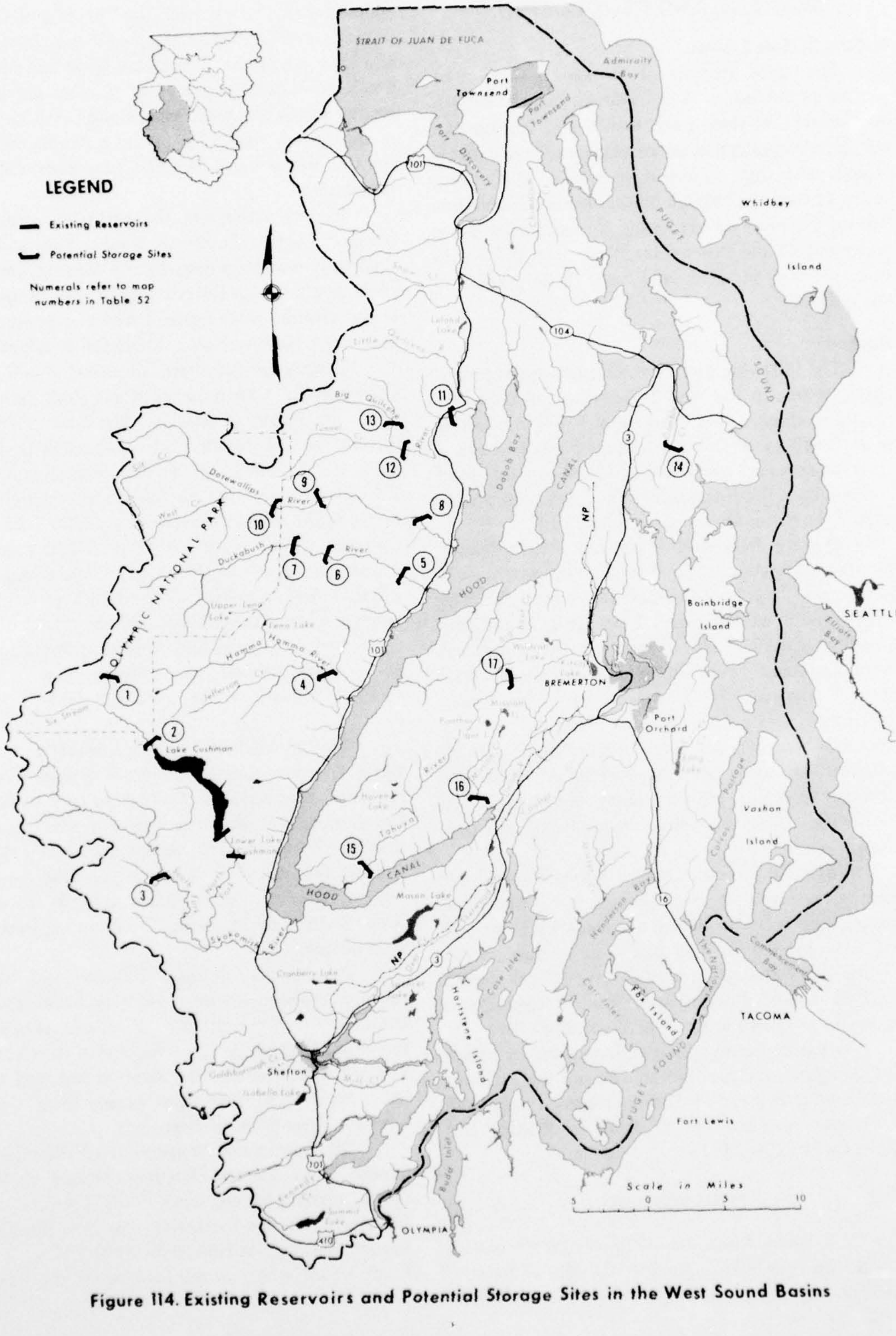


Figure 114. Existing Reservoirs and Potential Storage Sites in the West Sound Basins

TABLE 51.—Existing reservoirs in the West Sound Basins

Use: P, Hydro-electric development; R, recreation

Name	Location Stream, T-R-S	Drainage area (sq mi)	Storage (acre-ft) Active	Inactive and/or dead	Total	Dam dimensions Ht (ft)	Width (ft)	Reservoir area (acres)	Use	Applicant or owner	Remarks
Cushman Res. 1	N. F. Skokomish 22-4W-5	94	360,000	93,000	453,000	275	1,111	4,200	P, R	City of Tacoma	
Cushman Res. 2	N. F. Skokomish 22-4W-16	100	2,000	6,000	8,000	235	460	70	P	City of Tacoma	

TABLE 52.—Potential storage sites in the West Sound Basins

Map no.	Project name	T-R-S	River and mile	Total storage (1,000 acre-ft)	Drainage area (sq mi)	Remarks
1	Seven Streams	24-5W-18	N. F. Skokomish 29	--	26	
2	Staircase	23-5W-4	N. F. Skokomish 23	--	50	
3	Brown Cr.	22-5W-15, 21, 22	S. F. Skokomish 20	365	52	1,600 ac-ft water surface (City of Tacoma)
4	USGS site 9 (Hamma Hamma)	24-3W-21	Hamma Hamma R. S.	19	76	
5	Duckabush 15A	25-3W-2	Duckabush 4.8	73	66	
6	USGS site 14A (Big Hump)	25-3W-5	Duckabush 8.9	230-270	54	
7	USGS site 13	26-4W-1	Duckabush 10.5	--	47	
8	USGS site 12	26-2W-28	Dosewallips 3.3	120	109	
9	USGS site 11	26-3W-19	Dosewallips 12.6	--	76	
10	USGS site 10	26-4W-23	Dosewallips 15.1	--	70	
11	USGS site 18	27-2W-22	Big Quilcene R. 2.3	250	67	
12	Tunnel Cr.	27-2W-31	Big Quilcene R. 9.1	--	49	Diversion Dam at Tunnel Cr.
13	USGS site 16	27-2W-30	Big Quilcene R. 11.1	--	23.3	Diversion at Townsend Cr.
14	Gamble Cr.	27-2E-29	Gamble Cr.	20	62	
15	Tahuya R.	22-3W-12	Tahuya R.	111	42.2	
16	Mission Cr.	23-2W-25	Mission Cr.	9.5	12	
17	Gold Cr.	24-1W-21	Gold Cr.	9.7	1.4	Kitsap Co. PUD proposal

QUALITY OF SURFACE WATER

Chemical and Sanitary Quality

Surface water originating on the Olympic Peninsula in the western part of the West Sound Basins is generally excellent in chemical and sanitary quality. This area is essentially undeveloped, and the rivers are free of most man-made influences. Water-quality samples were collected intermittently from U.S. Highway 101 bridges spanning the Big Quilcene, Dosewallips, Duckabush, Hamma Hamma, and Skokomish Rivers for 7 years beginning in 1959. The results of the chemical analyses of samples from representative streams are summarized in Table 58.

Surface water on the Kitsap Peninsula is generally soft and contains less than 100 ppm of dissolved solids. Chico Creek (Table 58) is an example. However, a few streams such as Goldsborough Creek contain slightly greater concentrations of dissolved solids. The water of many of the smaller streams in the West Sound Basins, especially on the Kitsap Peninsula is highly colored at times. This yellow to amber color is attributed largely to organic solutes derived from swamps and poorly drained marshy areas.

The study area's streams are generally clear, except during high runoff. The maximum recorded turbidity, 80 JTU, was for the Dosewallips River. Although small glaciers exist in that stream's watershed, their melt water does not appreciably affect turbidity of the stream at its mouth.

Sanitary quality of streams in this region is generally excellent except below the cities and towns. For example, samples from the Dosewallips River at Brinnon had a maximum observed MPN coliform content of 230. The average MPN for Goldsborough Creek at Shelton was 900, and for Chico Creek near Bremerton, 1,415.

Stream Temperatures

Records of water temperature have been collected from 19 stations on 16 streams in the West Sound Basins. Temperatures are measured at two stations each on the North and South Forks Skokomish River. Of the 16 streams, 9 drain the east flank of the Olympic Mountains, and 7 drain parts of Kitsap County. Thermographs have been in operation at eight of the stations (Table 59).

Stream temperatures in the basins are significantly low. Watersheds of the mountain streams have a rather large percentage of high altitude area in comparison to basins east of Puget Sound and, therefore, remain cooler in summer. The flow in North Fork Skokomish River, however, is appreciably depleted by power diversions at Cushman Reservoir, and diminished flows downstream are easily warmed by solar radiation. Because streams that head in lowland parts of the study area are largely supported by ground-water during warm dry weather, their temperatures do not rise significantly in summer months.

Sediment Transport

Much of the terrain in the basins is mountainous and has extremely variable soil characteristics. In the mountainous areas, soils are normally shallow and stony, and extensive outcrops of bare rock are common. Soils in the lowlands are generally sandy and gravelly and are well drained, although some poorly drained soils exist along Puget Sound and in a few low-lying inland areas. Vegetative cover usually precludes excessive erosion. Where vegetation has been removed for urban development and road construction, additional erosion probably has been slight and of a temporary nature. Stream channels, mainly in their lower reaches, are cut into deposits of unconsolidated sand and gravel; this material is eroded and moved during periods of high runoff. Sloughing of banks occurs along most channels, particularly on the Skokomish River.

Suspended-sediment concentration in most streams of the study area is usually less than 20 ppm. Sediment data collected from the Skokomish River near Potlatch in 1965-66 indicate that the river transports about 100,000 tons of suspended sediment during an average year. It transports as much as 40,000 tons per day when the mean daily discharge exceeds 10,000 cfs. Sediment data on other principal rivers, the Dosewallips, Duckabush, and Hamma Hamma, indicate that each may transport about 4,000 tons of suspended sediment on the average.

Appreciable movement of bed materials occurs on the Skokomish River during periods of high runoff, but in the other principal rivers, the movement of bedload is less pronounced, and occurs mostly in lower reaches. Smaller streams are generally unable to transport large quantities of bed materials. Some of the eroded sediments are deposited in lakes and reservoirs.

GROUND WATER

Ground-water resources in the basins are discussed separately by the following geographic areas: northern lowlands; southern lowlands; and the mountains which include parts of Olympic National Park and Forest. The northern lowlands include areas on the Olympic Peninsula north of Mason County and north and east of the Olympic National Forest. The southern lowlands include the Kitsap Peninsula, its adjacent islands and the area on the Olympic Peninsula southeast of the national forest.

NORTHERN LOWLANDS

The most productive aquifers in the northern lowlands are in coarse Quaternary deposits, which occur discontinuously over about 200 square miles. Near Sequim the deposits exceed 2,000 feet in thickness and extend more than 1,000 feet below sea level. The aquifers presently used, however, are no deeper than about 600 feet below sea level. Most wells obtain ground water from within 100 feet of land surface.

Where Quaternary deposits are absent, ground-water is obtainable only from older consolidated rocks, in which well yields of 10 gpm or less can be expected.

Available geologic maps do not differentiate the various types of Quaternary sediments exposed at the surface. The subsurface materials, as inferred from drillers' logs, are predominantly outwash sediments that consist of coarse sand, gravel, and boulders. The saturated thickness of these coarse materials locally exceeds 70 feet. More than one layer of till is recorded in some logs, but the individual till layers

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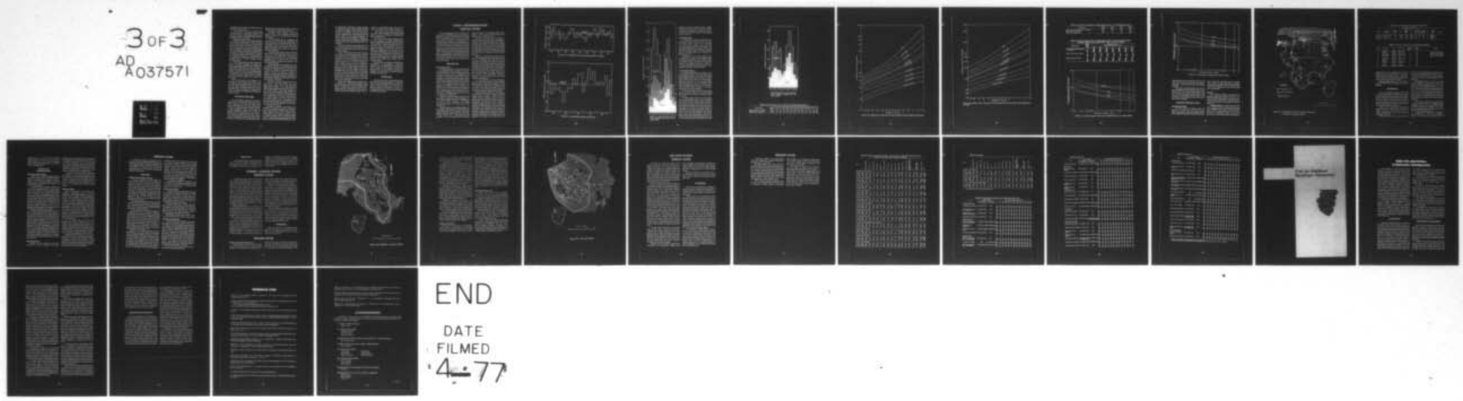

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are usually less than 40 feet thick. Many logs do not indicate the presence of till.

Most aquifers below till are confined under artesian pressure. At a land-surface altitude of less than about 200 feet, wells tapping them may flow, depending on whether the pressure surface is above or below land surface at the well site.

Recharge to aquifers in the northern lowlands is by infiltration of precipitation on the land surface and to a smaller degree, from the runoff of mountain streams. The amount of recharge is estimated to be about 5,000 acre-feet per year. On a long-term basis, however, probably less than one-half of that quantity can be intercepted by wells without causing salt-water encroachment problems. Opportunities for artificial or for induced recharge in the northern lowlands are not apparent from present data. At present, most of the ground water is probably discharged through submarine springs.

Limited water-quality data suggest that ground water in the northern lowlands is acceptable for almost all purposes. Dissolved-solids concentrations are generally 200-500 ppm, and water hardness is usually in the range from 120 to 180 ppm. Concentrations of silica are about 30 ppm. Objectionable concentrations of iron are seldom reported. Chloride is normally less than 10 ppm, except in shoreline areas where fresh-water aquifers may contain traces of sea water.

Most of the ground water pumped is for domestic and livestock use, but a few wells are used for irrigation and for dairy operations. Port Townsend has drilled large-capacity water wells, but its principal supply is still from surface water sources. Well yields as high as 720 gpm are reported in the northern lowlands, and pumping rates of 200 gpm or more are common.

SOUTHERN LOWLANDS

The most productive aquifers of the southern lowlands are coarse Quaternary deposits which are rather continuous over about 900 square miles. Locally, the sediments are more than a thousand feet thick. At other places they pinch out against outcrops of older consolidated rocks, such as along the Olympic Mountains foothills, in the vicinity of Bremerton and in southern Mason County. Quaternary aquifers containing fresh water may occur as much as a thousand feet below sea level, but the most productive water-bearing zones are generally less than 200 feet below sea level. Water levels in wells are generally less than 100 feet below land surface.

Quaternary deposits exposed at the surface consist mainly of till, recessional outwash, and alluvium. Outcrops of older Quaternary sediments occur locally.

Till is generally present as a capping on the lowlands. It also occurs at depth except below the deeper valleys and in a small area west of Shelton. At most places, till is less than 40 feet thick, and is seldom thicker than 80 feet. Because of its generally impervious character, the till does not contain any aquifers of importance.

Recessional outwash covers many of the valley floors, and is notably extensive in much of the area north and west of Oakland Bay. The outwash is composed of sand, gravel, silt, and clay. Recessional outwash may be as thick as 150 feet in the Skokomish Valley. In upland areas it generally is thin and contains little water.

Recent alluvium occurs principally in the Skokomish River flood plain, and consists mainly of fine sand and silt with minor amounts of clay and peat. Although the thickness of the alluvium may be as much as 100 feet, the thickness is difficult to determine at some places because the distinction of alluvium and underlying recessional outwash is somewhat arbitrary. Alluvium in the Skokomish Valley is saturated about to river level.

Quaternary sediments, older than the till, crop out on some of the slopes adjacent to the more deeply incised streams, and in most places along Puget Sound. Aquifers in the older Quaternary sediments are generally more productive than those in the post-till sequence; where these sedimens are coarse, zones of saturated sand and gravel 100 feet or more in thickness are common. In the northern part of the Kitsap Peninsula, however, the older aquifers are composed mainly of fine sand, and they yield only small amounts of water. Deep aquifers in the older Quaternary sediments are confined under layers of clay or till, and wells completed in these aquifers in low-altitude areas may flow.

Practically all recharge to the aquifers is by infiltration of precipitation. Aquifers in the southern lowlands may receive an average annual recharge of about 120,000 acre-feet. Of this amount, about 50,000 acre-feet may recharge the aquifers beneath the Olympic Peninsula. Of the remaining 70,000 acre-feet, which recharges aquifers beneath the Kitsap Peninsula, probably less than 40,000 acre-feet could

be intercepted by wells without causing salt-water encroachment problems. Owing to limited availability of surface-water supplies, either induced or artificial recharge to ground-water reservoirs would seem to have only marginal value on the Kitsap Peninsula and adjacent islands. On the Olympic Peninsula, the amount of annual rainfall available for recharge may be great enough—and the foreseeable demand small enough—that artificial recharge probably need not be considered.

Most natural ground-water discharge is into the larger streams, particularly in their lower reaches, and into Puget Sound through springs above and below the level of tidewater.

Water in most aquifers in the southern lowlands is generally low in dissolved solids, and is acceptable for practically all uses. Dissolved-solids contents in most places are less than 100 ppm, but they exceed 200 ppm in some of the shoreline areas where the aquifers contain traces of sea water. Hardness of water is generally less than 60 ppm, and generally does not exceed 120 ppm. Silica concentration is generally in the 10 to 20-ppm range on the Olympic Peninsula and in the 20 to 40-ppm range on the Kitsap Peninsula and adjacent islands. Iron exceeding 0.1 ppm is common in eastern parts of the Kitsap Peninsula and in the southern parts of Vashon and Maury Islands. However, reports from well owners indicate that concentrations of iron are rarely high enough to be objectionable.

Aquifers that underlie glacial till supply water for industrial use at Bremerton and Shelton. These aquifers also supply most of the municipal demand except at Shelton whose supply is largely from a spring issuing from recessional outwash. Aquifers in recessional outwash and alluvium supply water for irrigation in the Skokomish Valley, about the only place in the lowlands where irrigation is significant.

In this study area, most wells are less than 300 feet deep; several municipal and industrial-supply wells in the vicinity of Bremerton and Shelton are 500 to 1,000 feet deep.

Most wells in the southern lowlands produce less than 1,500 gpm. The largest recorded yield is from an industrial well in Shelton which was tested at 4,160 gpm with a water-level drawdown of 63 feet. Figure 23 shows order-of-magnitude estimates of expected well yields in the Study Area. In areas where Quaternary sediments are very thin, such as near outcrops of consolidated rocks, well yields of only 10 gpm or less can be obtained. On the northern end of the Kitsap Peninsula, fineness of aquifer materials mostly precludes development of adequate supplies; moreover these aquifers often contain water of undesirable quality.

At present the main problem of ground-water development is the contamination of fresh-water aquifers in areas near Puget Sound as a result of salt water intrusion. In the vicinities of Shelton and Bremerton the rather large amount of ground-water pumping in the past may have caused some inland movement of the salt water.

MOUNTAINS

The mountainous area in the Olympic National Park and Forest consists principally of consolidated rocks. In this area well yields of 10 gpm or less can be expected. Such low yields do not, however, constitute a problem. The mountains are devoted to recreational activities, for which only a small amount of potable water is needed.

ELWHA—DUNGENESS BASINS

SURFACE WATER

The Elwha-Dungeness Basins comprise 797 square miles, including 700 square miles of land and inland water. A map of the Basins is shown in Figure 123. The Elwha River Basin, the largest in the study area, occupies 321 square miles. Some tributaries of the Elwha originate in glaciers on the higher peaks of the Olympic Mountains. The Dungeness River drains 198 square miles. Most of the drainage area of these streams is in the heavily forested and extremely rugged Olympic National Park and Olympic National Forest. The rivers leave their mountainous catchment areas at the boundaries of the National Forest and descend through lowlands to their outlets at the Strait of Juan de Fuca. Between these two river basins are several small creeks draining a 170 square-mile foothill and coastal plain.

STREAMFLOW

Runoff Characteristics

The greatest quantities of runoff from lands in the Elwha-Dungeness Basins originate in the vicinity of the high central core of the Olympic Mountains complex. Although records of streamflow in the mountains are nonexistent, average annual runoff is estimated to exceed 160 inches in the upper reaches of the Elwha and Dungeness Rivers. Runoff decreases rapidly to the north and east where the rain shadow effect of the Olympic Mountains becomes pronounced. The shielding by these mountains is so effective that runoff in the Sequim area averages less than 15 inches a year. Mean annual runoff for the entire Elwha-Dungeness study area amounts to about 45 inches, or 1,700,000 acre-feet from an area of approximately 690 square miles.

During the period 1931-60, runoff from the Elwha River drainage above McDonald Bridge near Port Angeles averaged 1,498 cfs or 1,090,000 acre-feet per year. This is equivalent to an average unit-runoff production of 5.6 cfs per square mile of drainage area.

Records obtained on the Dungeness River near Sequim during the period 1937-63 and adjusted for the standard period 1931-60, indicate that annual runoff in this area averages about 382 cfs or about 277,000 acre-feet. On a unit-runoff basis this amounts to 2.4 cfs per square mile. The noticeably lower unit-runoff for the Dungeness River reflects basically a lower elevation and a generally more intense lee-side or rain-shadow effect.

Variations in annual runoff are depicted in Figures 115 and 116 in terms of yearly discharges for the Elwha River at McDonald Bridge and the Dungeness River near Sequim. The lowest yearly discharge for Elwha River of 859 cfs, which occurred during the 1944 water year, amounts to 57% of the standard long-term mean (1931-60). By comparison, the highest average flow of 2,050 cfs, which occurred during the 1954 water year, represents 137% of the long-term mean.

Bar charts of mean monthly discharges for the Elwha and Dungeness Rivers are provided in Figures 117 and 118. Although widely different flows were measured at these gaging sites, similar seasonal trends are evident. Flows in both streams peak during the winter period of high precipitation, and again during late spring and early summer when a combination of snowmelt and spring rains is the major contributor. As an average, the greatest monthly flows occur in May and June; however, the highest monthly flow ever recorded on the Elwha River occurred in December. In general, winter flows in this region exhibit the most variability.

As is characteristic for Western Washington, both the Elwha and Dungeness exhibit minimum flows during the summer, when precipitation is least and snowpacks are depleted. A few small permanent ice fields dot the high mountainous parts of this study area, and they provide a modest contribution to streamflow during the summer low-flow period.

Annual runoff characteristics of the Elwha and Dungeness Rivers are similar in general. Streamflow usually begins to increase in October from the summer base flow. Streamflow during the October-March period is characterized by a series of sharp rises superimposed on base flow, which is highest in December. Runoff generally decreases from January through the middle of March as a result of decreased precipitation. As temperatures begin rising in the latter part of March, snowmelt causes an increase in streamflow, which reaches a maximum normally in early June. Following the snowmelt peak, streamflow recedes to minimum base flow usually be the end of September. A reservoir on the Elwha River used

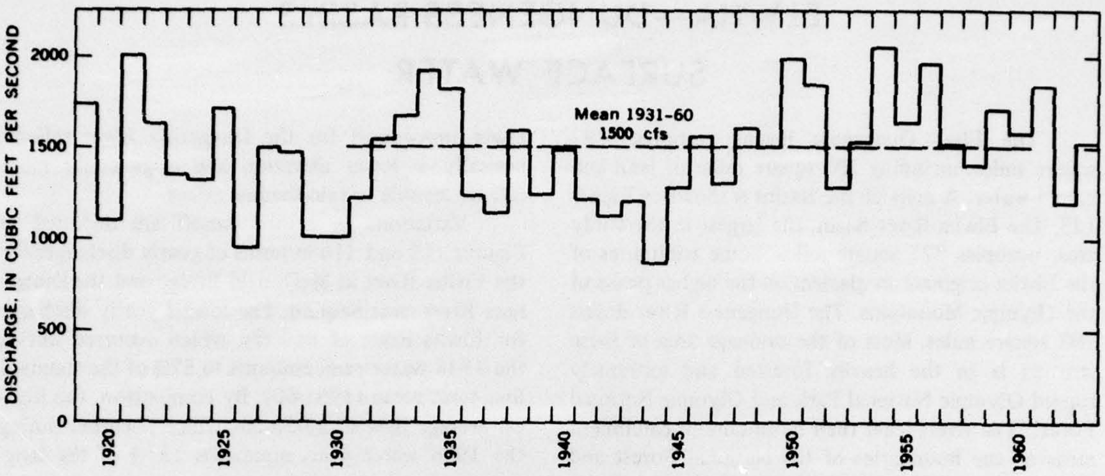


FIGURE 115.–Annual discharges, Elwha River at McDonald Bridge near Port Angeles.

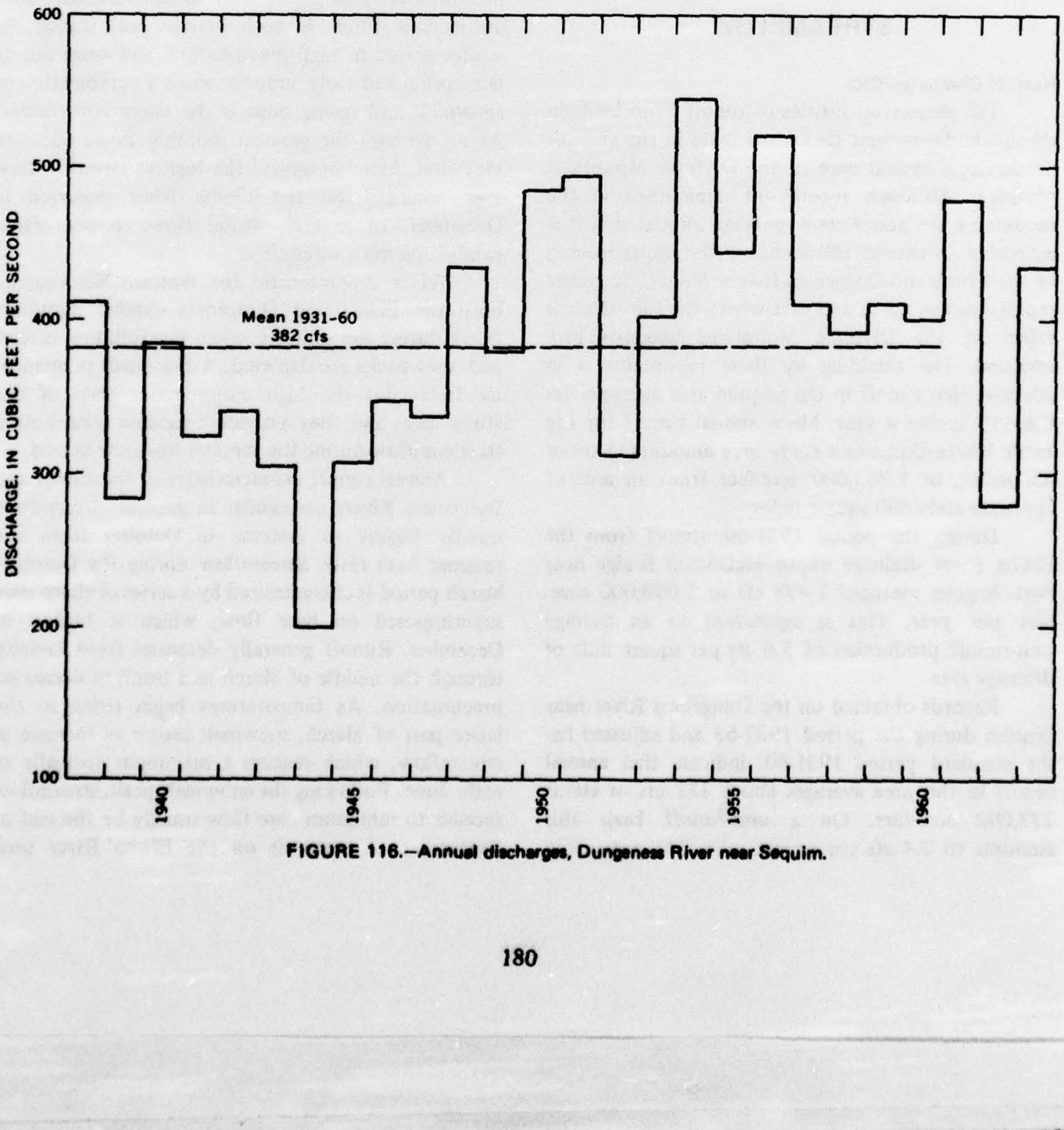


FIGURE 116.–Annual discharges, Dungeness River near Sequim.

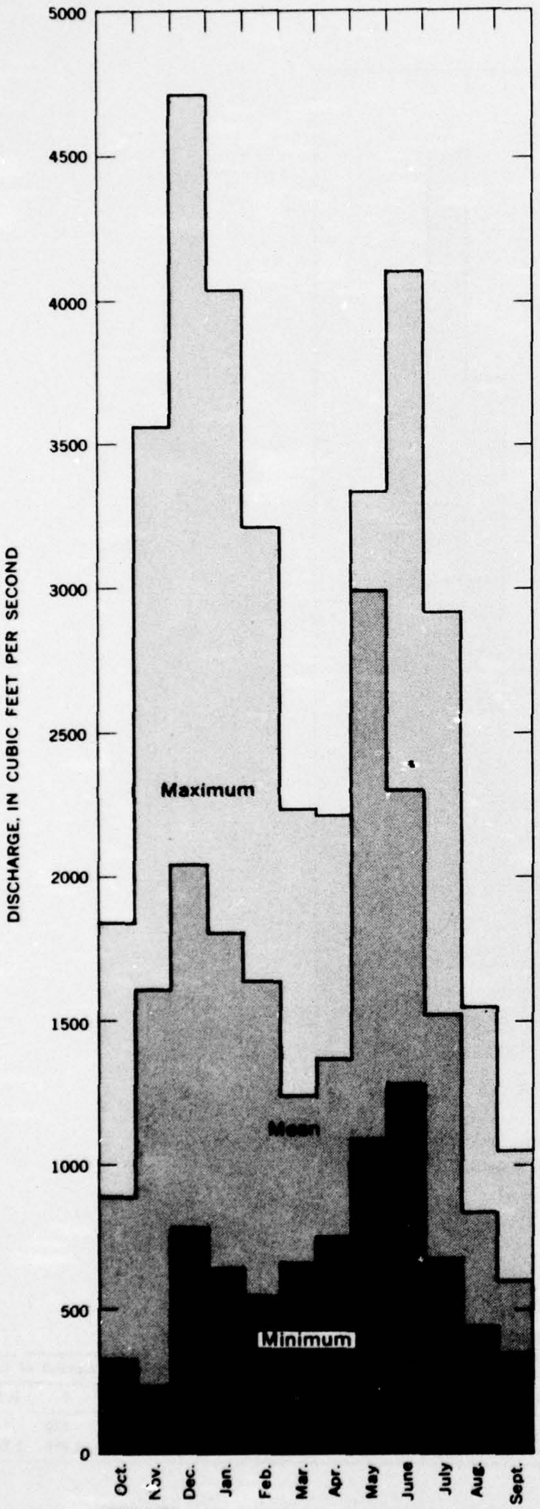


FIGURE 117.–Maximum, mean and minimum monthly discharges, Elwha River near Port Angeles, 1931-60.

primarily for power production causes a slightly higher-than-natural base flow during the summer. Variability of the daily flow of streams in the basins is presented as flow-duration data for selected gaging stations in Table 53.

Flood Characteristics

Floods caused by excessive rainfall and accompanying snowmelt are shown by sharp rises followed by recessions almost as rapid. Two or more peaks often occur within a period of two weeks. The maximum discharge recorded on the Dungeness River near Sequim was 8,400 cfs, on January 15, 1961. The maximum discharge recorded at the McDonald Bridge gage on the Elwha River was 41,600 cfs, on November 18, 1897.

Probability curves of annual maximum flows for specified time periods for the Dungeness River near Sequim and the Elwha River near Port Angeles are presented in Figures 119 and 120. The periods of record for the Dungeness River near Sequim are 1925-30 and 1938-64. For the Elwha site, the record periods are 1898-1900, 1901, and 1919-64.

Low-Flow Characteristics

Low-flow characteristics of streams in the Elwha-Dungeness Basins were compared using indexes from low-flow frequency curves from three gaging stations (Table 54). The low-flow indexes are excellent in the Elwha River basin, fair in the Dungeness River Basin and poor in the low-lying streams tributary to the Strait of Juan de Fuca (Fig.22). The slope and spacing indexes which show the variability of low flows are about the same for all streams; slightly less than the regional average.

Low-flow frequency data for the three gaging stations are listed in Table 55 and frequency curves for the two of the three stations are shown in Figures 121 and 122.

The large low-flow index of 1.56 cfs per square mile for the Elwha River is due to reservoir regulation and retarded runoff from large amounts of precipitation, much of which is stored as snow. In contrast, Siebert Creek has an index of only 0.16 cfs per square mile, which is attributed to the small amount of precipitation in the basin, little of which is stored as snow. All of the low-lying tributaries to the Strait of Juan de Fuca may have similarly small indexes because their basin characteristics are like those of Siebert Creek watershed. The Dungeness River basin is in the rain shadow of Mount Olympus, and receives

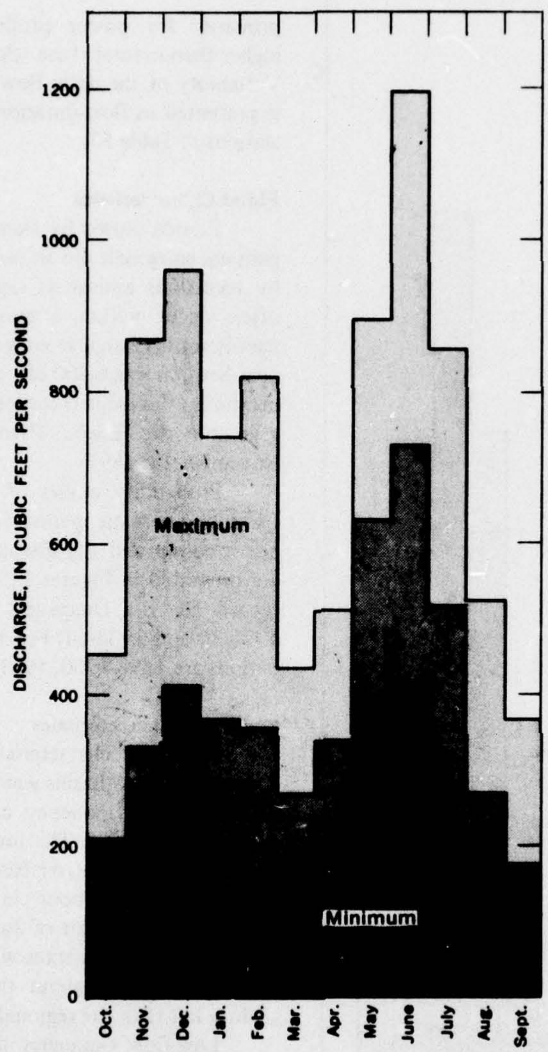


FIGURE 118.—Maximum, mean and minimum monthly discharges, Dungeness River near Sequim, 1931-60.

TABLE 53.—Flow-duration data for streams in the Elwha-Dungeness Basins

Gaging station	Period of analysis	Flow, in cubic feet per second, which was equaled or exceeded for indicated percent of time											
		99	95	90	80	70	50	30	20	10	5	1	0.1
Siebert Creek near Port Angeles	1953-64	2.3	2.7	3.1	4.0	5.2	8.8	15	21	36	58	170	640
Dungeness River near Sequim	1938-65	100	120	140	172	210	300	440	550	740	920	1,480	2,700

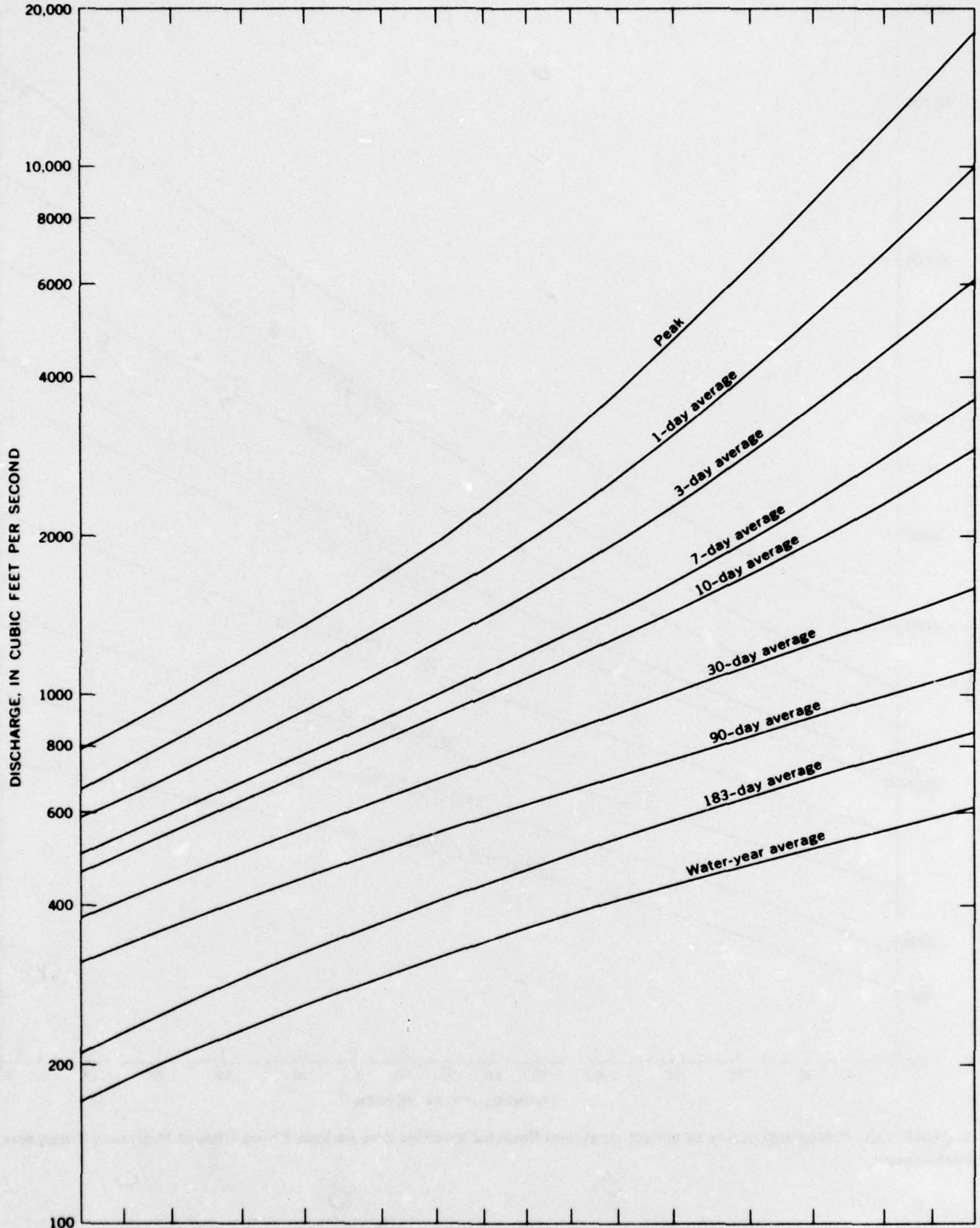


FIGURE 119.—*Probability curves of annual maximum flows for specified time periods, Dungeness River near Sequim.*

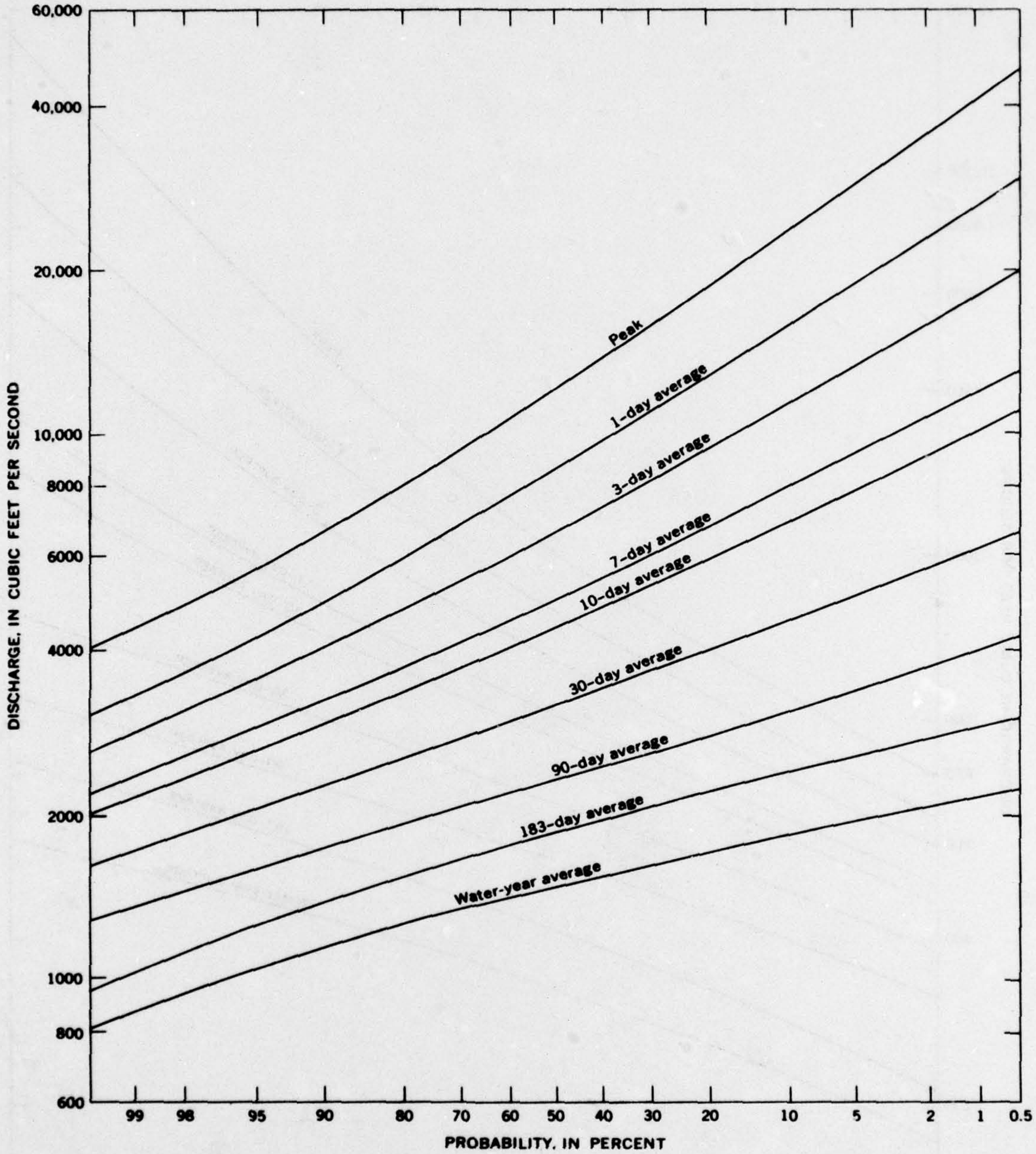


FIGURE 120.—Probability curves of annual maximum flows for specified time periods, Elwha River at McDonald Bridge near Port Angeles.

TABLE 54.—Low-flow characteristics for selected gaging stations in the Elwha-Dungeness Basins

Gaging Station	Drainage area	Low-flow index	Slope index	Spacing index
Elwha River at McDonald Bridge near Port Angeles	269	1.56	1.62	2.01
Siebert Creek near Port Angeles	15.5	.16	1.39	2.28
Dungeness River near Sequim	156	.79	1.40	2.33

TABLE 55.—Low-flow frequency data for selected gaging stations in the Elwha-Dungeness Basins
[Discharge adjusted to base period April 1, 1946, to March 31, 1964]

Gaging station	Number of consecutive days	Streamflow in cfs, for indicated recurrence intervals, in years						
		1.05	1.30	2.0	5	10	20	30
Elwha River at McDonald Bridge near Port Angeles	7	620	500	420	340	300	260	245
	30	720	590	500	415	375	340	330
	90	1,350	970	740	560	490	440	420
	183	1,900	1,460	1,180	930	840	760	720
Siebert Creek near Port Angeles	7	3.9	3.0	2.5	2.0	1.9	1.8	1.7
	30	4.4	3.4	2.8	2.3	2.2	2.1	2.0
	90	6.6	4.7	3.7	2.9	2.6	2.4	2.3
	183	11.3	7.4	5.7	4.5	4.1	4.0	3.9
Dungeness River near Sequim	7	168	141	123	104	95	88	84
	30	198	163	141	120	109	101	97
	90	307	245	203	160	141	126	119
	183	495	360	287	232	210	200	193

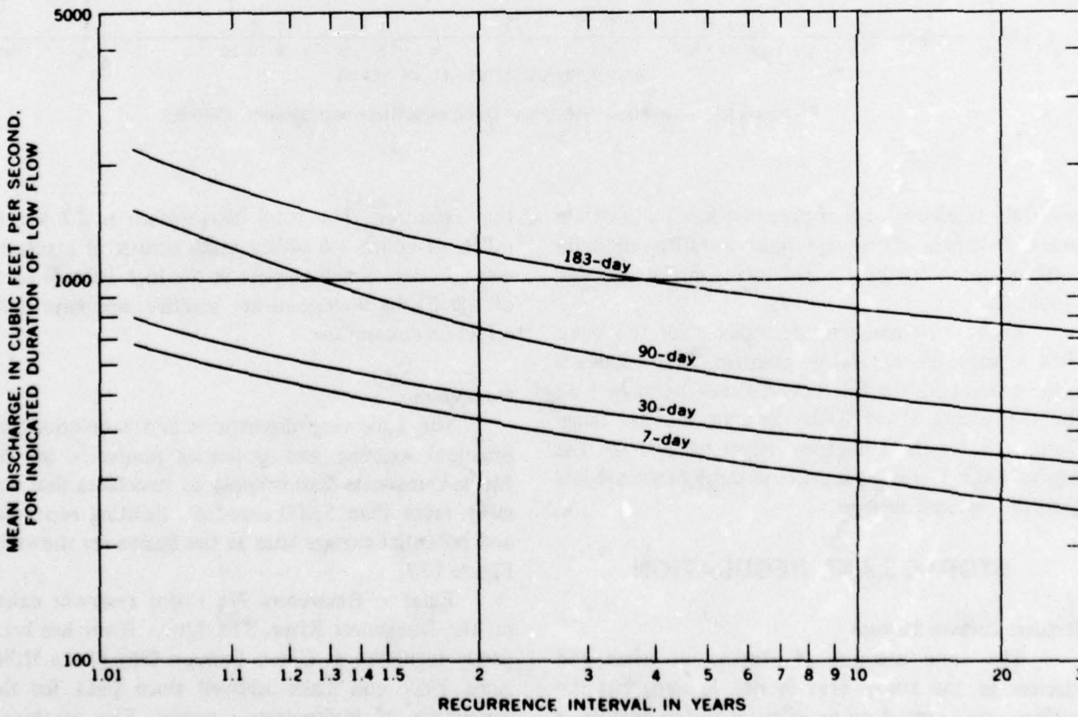


FIGURE 121.—Low-flow frequency, Elwha River at McDonald Bridge near Port Angeles, 1946-63.

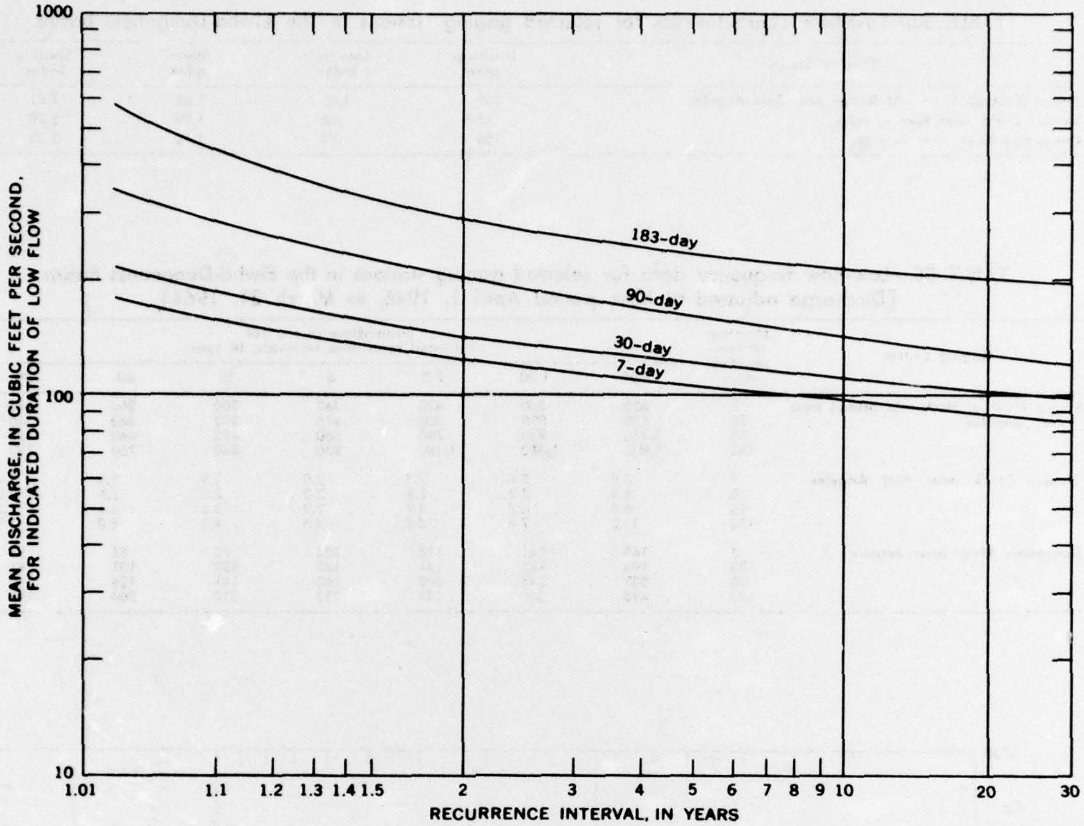


FIGURE 122.—Low-flow frequency, Dungeness River near Sequim, 1946-63.

relatively small amounts of precipitation. Its low-flow index—0.85 cfs per square mile—is rather small in comparison to those of other basins in the Olympic Mountains.

Both slope and spacing indexes for the three sites investigated are fairly uniform. Slope indexes range from 1.39 for the Siebert Creek basin to 1.62 for the Elwha River basin. Spacing indexes range from 2.16 for the Dungeness River to 2.81 for the Elwha River. The slope indexes in these basins are less than the regional average.

STORAGE AND REGULATION

Natural Surface Storage

The total amount of storage in lakes and glaciers in the study area is not known, but the surface area covered by these water bodies provide at least a comparative indication of the amount of water that is stored. The total lake surface is 2.2 square miles, of which 1.6 square miles consist of regulated water bodies. Small glaciers in the high-altitude areas of the Elwha watershed are inactive, and have little effect on streamflow.

Reservoirs

The following discussions and tabulations of principal existing and potential reservoirs in the Elwha-Dungeness Basins apply to structures that can store more than 5,000 acre-feet. Existing reservoirs and potential storage sites in the Basins are shown in Figure 123.

Existing Reservoirs—No major reservoir exists on the Dungeness River. The Elwha River has been partly regulated at Glines Canyon Dam (Lake Mills) since 1927 and Lake Aldwell since 1911 for the generation of hydroelectric power. The combined total storage of these private power developments is

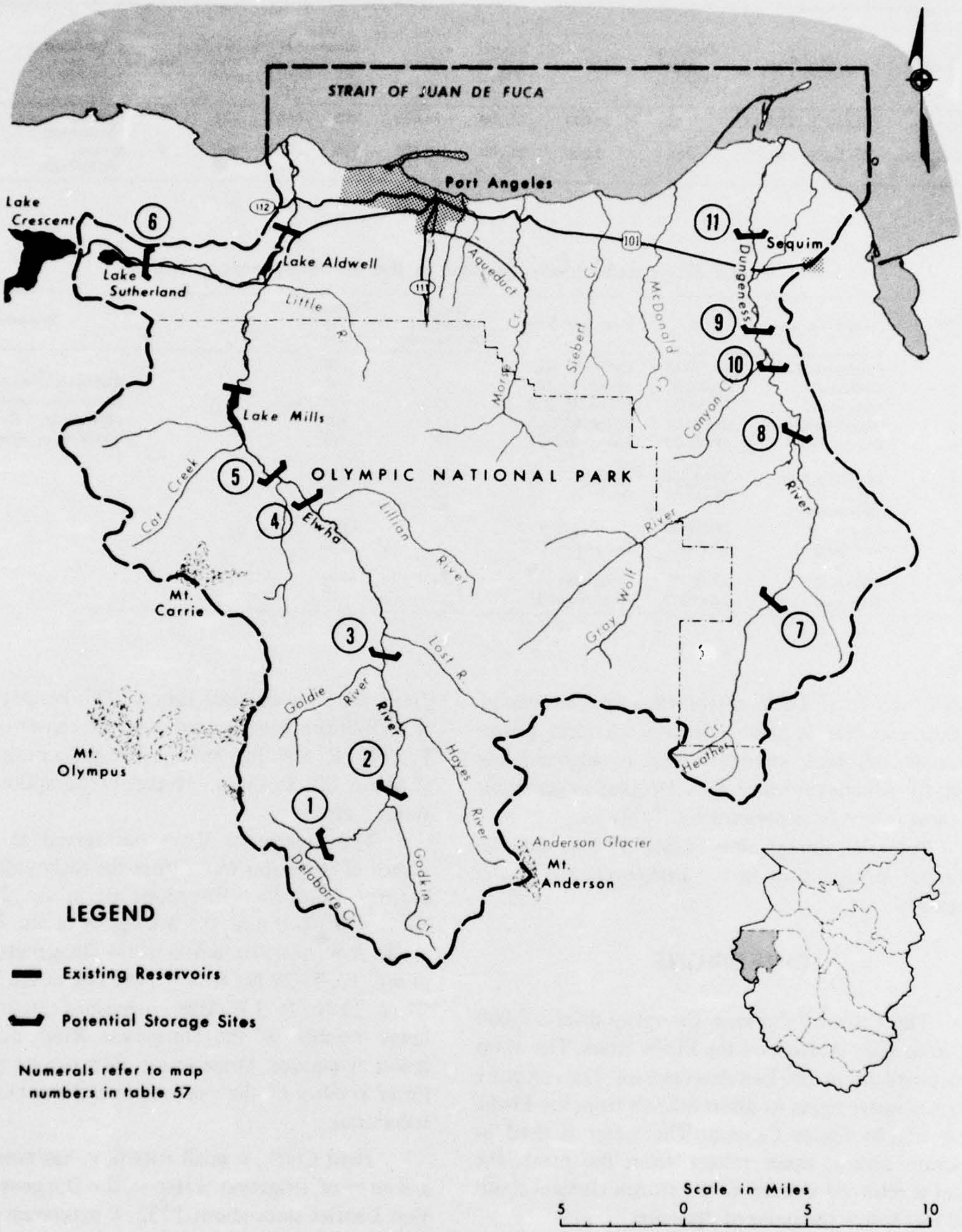


Figure 123. Existing Reservoirs and Potential Storage Sites in the Elwha – Dungeness Basins

TABLE 56.—Existing reservoirs in the Elwha-Dungeness Basins

P, Hydro-electric development

Name	Location Stream, T-R-S	Drainage area (sq mi)	Storage (acre-ft) Active	Inactive and/or dead	Total	Dam dimensions Ht (ft)	Width (ft)	Reservoir area (acres)	Use	Applicant or owner	Remarks
Mills Lake	Elwha R. 29-7-17	245	26,000	13,000	39,000	200	555	435	P	Crown-Zellerbach	
Aldwell Lake	Elwha R. 30-7-15	314	3,000	27,000	30,000	110	497	580	P	Crown-Zellerbach	

TABLE 57.—Potential storage sites in the Elwha-Dungeness Basins

Map no.	Project name	T-R-S	River and mile	Total storage (1,000 acre-ft)	Drainage area (sq mi)	Remarks
1	Delabarre Cr.	26-7W-13	Elwha R. 40	--	16	
2	Godkin Cr.	26-6W-9	Elwha R. 35	--	41	Diversion below Goodman Cr.
3	Press Valley	27-6W-9	Elwha R. 27.8	72	106	235-ft dam below Goldie R.
4	Grand Canyon	28-7W-12	Elwha R. 18.6	--	163	430-ft dam below Lillian R.
5	Geyser Basin	29-7W-34	Elwha R. 15.8	87	196	330-ft dam above Fitzhenry Cr.
6	Lk. Sutherland	30-8W-22	Indian Cr. 5.1	30	133	
7	Upper Dungeness	28-4W-35	Dungeness 24	--	38	
8	Grey Wolf	29-3W-30	Dungeness 15.3	116	148	
9	Carlsborg	29-4W-1	Dungeness 11		156	
10	Caraco Cr.	29-4W-13	Dungeness	25	150	
11	Finn Hall	30-4W-23	Dungeness 5	--	179	

69,000 acre-feet. Their combined active storage of 29,000 acre-feet is used primarily to meet power demands, but some storage is used to augment low flows for fisheries enhancement. Detailed information on these reservoirs is presented in Table 56.

Potential storage sites—Table 57 lists data on potential storage sites in the Dungeness and Elwha drainages.

DIVERSIONS

The Crown Zellerbach Company diverts 2,000 cfs from Lake Aldwell on the Elwha River. The water is returned about 200 feet downstream. The company also has water rights to divert 800 cfs from the Elwha at a site in Glines Canyon. The water is used to generate power; upon release from the plant, the water is returned directly to the stream channel about 600 feet below the point of diversion.

The city of Port Angeles diverts water from the Elwha River about 3 miles above its mouth, and delivers as much as 115 cfs, primarily for use in several industrial plants. After use, the water is discharged to tidewater.

Port Angeles also obtains water from Morse Creek for its municipal supply. This system consists of a diversion dam located near the center of sec. 5, T. 29 N., R. 5 W. In 1967 the city had a peak demand of about 20 cfs and an average consumption rate of about 6 cfs.

The Dungeness River has served as a major source of irrigation water since the early years of this century. Four ditch diversions are in sec. 26, T. 30 N., R 4 W., two near the W¼ corner of sec. 35, T. 30 N., R. 4 W. near the mouth of the Dungeness Canyon in sec. 12, T. 29 N., R. 4 W., and one in the SE¼ sec. 30, T. 29 N., R. 3 W. These diversions can dry up the lower reaches of the Dungeness River during the low-flow periods. Some return flow occurs along the lower reaches of the main stem and several lowland tributaries.

Herd Creek, a small tributary, has been used as a source of irrigation water in the Dungeness Irrigation District since about 1933. A maximum of 10 cfs is diverted from the creek in NW¼ sec. 12, T. 30 N., R. 4 W. A small amount of the water returns to lower Herd Creek and the Dungeness River.

A fish hatchery adjacent to the Dungeness River is NW¼ sec. 12, T. 29 N., R. 4 W. diverts as much as 25 cfs from two alternate points in

NE¼SW¼ of sec. 12, T. 29 N., R. 4 W. The water bypasses about 0.75 mile of the river. the city of Sequim diverts up to 1.4 cfs from the Dungeness River in the NE¼ of the NW¼ of sec. 12, T. 29 N., R. 4 W. for municipal supply.

QUALITY OF SURFACE WATER

Chemical and Sanitary Quality

Surface water in the Elwha-Dungeness Basins is of excellent chemical quality in virtually all respects. Owing to ground-water contributions, streams in lowland areas of the basins generally have mineral contents that are slightly higher than average for the Puget Sound Study Area.

As listed in Table 58, samples collected from the Elwha and Dungeness Rivers on a quarterly basis from 1959 to 1966 show that maximum dissolved solids concentrations were 54 ppm for the Elwha River and 94 ppm for the Dungeness River. These rivers contain soft water (less than 60 ppm) most of the time; values of hardness are somewhat greater for the Elwha River than for the Dungeness. Except during periods of high runoff the streams are clear and have an average turbidity of 10-12 JTU. The maximum turbidity observed was 65 JTU, for the Dungeness River. Apparently the small glaciers in the Elwha Basin have little effect on turbidity.

Because the Elwha-Dungeness Basins are principally in undeveloped areas, the sanitary quality of these streams is generally excellent. Data collected on a quarterly basis from 1959 to 1966 for both rivers indicate that the streams have low MPN values of coliform bacteria–generally less than 100. The maximum MPN of coliform bacteria for the Elwha River during the sampling period was 430; for the Dungeness it was 230. The sampling site on the Elwha River is near its mouth, whereas the Dungeness River site is near the Olympic Mountains. Therefore, the sanitary-quality data for these major streams provide a comparative indication of the present effects of urban and agricultural development in the lowland area between the Olympic Mountains and the Strait of Juan de Fuca.

Stream Temperatures

Records of water temperatures have been analyzed for only two streams in The Elwha-Dungeness Basins: the Elwha near Port Angeles, and the Dungeness near Sequim (Table 59). Of the two, the Elwha is generally 1° F to 4° F warmer during most months. The highest temperature attained for the period of record was 63 F in August. The warmer temperature of the Elwha River may in part attributed to stabilizing effects of Lake Mills, a power reservoir located above the Port Angeles station.

Temperatures of both streams are generally low in comparison to other streams investigated. This is partly because of the predominantly high altitude and northern latitude of the two watersheds. Also, the streams are among the few in the Puget Sound Area that are north-south oriented, and afford less exposure to solar radiation than east-west oriented streams.

Sediment Transport

Most of the land area in this study area is comprised of mountainous terrain with extremely variable soils. In the higher altitudes, the soils are generally stony and shallow. At lower altitudes, they consist of silt, sand and gravel formed from fluvial reworking of glacial outwash. The higher altitudes receive large amounts of precipitation , but excessive erosion of soils is largely precluded by a profuse cover of vegetation. In the lower altitudes where urban development, road construction, logging, and farming have resulted in the removal of vegetation, sheet or rill erosion of fine sediments occurs during periods of intense rain. Some channel erosion by bank sloughing and bed movement also occurs, principally in areas where streams cut into glacial drift deposits near the Strait of Juan de Fuca.

The two largest rivers in the basin, the Dungeness and the Elwha, transport most of the eroded sediment. The Elwha River transports about 25,000 tons of suspended sediment during a year of normal streamflow. In contrast, the Dungeness River probably transports less than 1,000 tons of sediment in an average year. Suspended-sediment concentrations in most streams is generally less than 20 ppm.

Sediment problems generally are local in nature and result from removal of vegetation in logging or construction operations. Future sediment transport characteristics of streams will probably not change appreciably from present conditions because much of the study area is within the Olympic National Park and should, therefore, remain undisturbed.

GROUND WATER

Ground-water supplies are plentiful in a few places in both the mountains and the lowlands of the Elwha-Dungeness Basins. The lowlands are those areas that lie generally below an altitude of 1,000 feet and are marginal to the Strait of Juan de Fuca; the Olympic Mountains are considered as the remaining higher areas to the south.

LOWLANDS

Geology and Ground Water Occurrence

The most productive lowland aquifers are coarse Quaternary deposits that are continuous over about 90 square miles. Thicknesses of Quaternary sediments are greater near the Strait of Juan de Fuca, where locally some deposits are at least 2,800 feet thick. The deposits decrease in thickness to the south, and thin to a feather-edge at outcrops of older consolidated rocks that form the Olympic Mountains. The Quaternary sediments contain fresh water aquifers as much as 500 feet below sea level. Generally, ground water can be obtained less than 100 feet below land surface.

Quaternary material exposed at the land surface is mostly recessional outwash that in some places has been reworked by streams. The resulting accumulations of fine sediments range in thickness from less than 20 feet to as much as 80 feet.

In the subsurface, the Quaternary sequence is so complicated that the occurrence of particular sedimentary units is difficult to predict. The presence of till deposits has not been established, although till-like clay has been recorded for intervals of more than 100 feet in some wells. Artesian aquifers of gravel and sand commonly underlie the clay, but places where flowing wells could be completed in these aquifers are not predictable. The shallowest aquifers exhibit water-table conditions, and in many places perched on beds of clay or silt.

Recharge to the aquifers is mainly by direct precipitation on the fairly permeable soils. Runoff from the Olympic Mountains may also contribute substantial amounts of recharge, particularly in areas near the mountains. The amount of natural recharge to aquifers in the lowlands may be about 10,000 acre-feet per year. Probably no more than one-half of this recharge could be intercepted by wells, owing to the steep hydraulic gradients which exceed 100 feet per mile in most places. The potential recharge is probably greatest in the western part of the study area, where the annual rainfall is high. However, ground-water availability in the western areas appears limited by the rather small areal extent of Quaternary aquifers. Locally, some of the water applied to irrigated crops percolates to the water table. In the Dungeness water shed, seepage from irrigation water has caused a rise in the water table of as much as 3 feet during the summer months. Opportunities to improve ground-water availability in the basin by artificial recharge seem negligible.

Ground-water movement is generally to the north where natural discharge occurs below sea level into the Strait of Juan de Fuca. No springs have been inventoried in this study area.

Quality of Ground Water

Limited data on the chemical quality of ground water provides information principally on chloride concentration and hardness. On the basis of 23 incomplete chemical analyses, chloride concentration ranges from 2 to 30 ppm, but is generally less than 10 ppm. Hardness ranges from 26 to 169 ppm, and commonly is between 60 and 120 ppm.

Sea-water intrusion has occurred at an abandoned 430-foot industrial well on the shoreline near Port-Angeles. The well was pumped at a rate of 320 gpm, and initially produced water with a chloride concentration of only 5 ppm; but after 7 years of pumping, chloride has increased to 550 ppm.

Objectionable concentrations of iron in water are occasionally reported by owners of shallow wells.

Utilization and Development

Use of ground water for irrigation in the study area is mainly in the areas of moderate relief east of Port Angeles. The only development of ground water for municipal use is an infiltration gallery in alluvial deposits along the Dungeness River. Water from this source is diverted to the city of Sequim. Relatively little water is pumped from small-capacity wells for individual household use. Irrigation wells generally have the greatest pumping rates, which are usually 200 gpm or less. Figure 23 shows order-of-magnitude estimates of expected well yields in the study area; owing to the complexity of subsurface deposits, however, yields locally can be either much greater or much less than those indicated on the map.

Most wells in the basin are less than 50 feet deep, and few are deeper than 100 feet.

MOUNTAINS

In the Olympic Mountains, Quaternary deposits occur in small areas totaling 10 square miles or less. The deposits occur mainly in the Siebert Creek watershed and in the general area of Indian Creek, a tributary to the Elwha River. Adequate supplies of ground water for domestic purposes are probably obtainable from these deposits in most places. Elsewhere, ground water is available only from consolidated rocks, in which well yields of 10 gpm or less can be expected.

WHIDBEY—CAMANO ISLANDS

SURFACE WATER

The Whidbey-Camano Islands study area consists of Island County (Figure 124), and includes two major islands, Whidbey and Camano, which comprise about 165 and 45 square miles, respectively. Both islands are long and narrow, and no point on either is more than 2½ miles from the sea. Most of the land surface is rolling uplands that generally range in altitude from 100 to 300 feet, but may exceed 500 feet in some places. The islands have a poorly developed stream network and rather small runoff. Dense evergreen vegetation, which covers much of the area retards surface drainage. Another indication of poor surface drainage is the large number of swamps and marshes found not only in lowland areas but also across scattered upland areas.

Because the islands lie in the rain shadow of the Olympic Mountains, generally less than 20 inches of precipitation falls annually, and there is virtually no accumulation of snowpack. Because of small amounts of precipitation and small size of stream basins (usually less than a few square miles), surface runoff is scanty, and many streams flow only intermittently.

Little information is available on the surface-water resources of the Whidbey-Camano Islands, and ground water constitutes the principal supply. Low flows of streams are supported by contributions from ground-water storage. Rapid runoff that might cause damaging floods is precluded by a dense cover of evergreen vegetation on the islands. Lakes in the study area comprise 1.4 square miles, and there are no major storage projects. Future development of surface-water resources will necessarily be limited to small scale local projects, and possibly will depend on the importation of water from outside the islands.

Quality of the surface water is probably satisfactory except in a few places.Water in most of the lakes appears to be excellent in chemical quality; however, a seemingly high degree of mineralization in Cranberry Lake prompted a chemical analysis that showed a chloride concentration of 37 ppm. High chloride in the lake may have resulted from ground-water inflow, because well waters in the vicinity contain 26 to 93 ppm of chloride. Sanitary-quality data are not available; but sewage disposal is principally through septic tanks, and some of the domestic wastes discharged to them undoubtedly move into the surface-water system.

Sediment problems in the islands occur in only a few localized areas where construction or farming have resulted in erosion owing to the removal of vegetation. Soils are generally well drained, and consist of materials largely derived from glacial and nonglacial sand, gravel, and some clay. A profuse cover of vegetation generally precludes excessive erosion during periods of intense rain.

DIVERSIONS

Water right records for the Whidbey-Camano Islands do not indicate any diversions of 5 cfs or more and most developments in this area involve diversions of less than 1 cfs.

GROUND WATER

Geology and Ground Water Occurrence

Coarse Quaternary deposits, which cover almost the entire land area of about 210 square miles, contain most of the aquifers in the islands. However, Quaternary sediments in the Whidbey-Camano Islands are generally finer than those in most other parts of the Study Area. Their total thickness may be 2,000 feet or greater, but fresh water aquifers are not

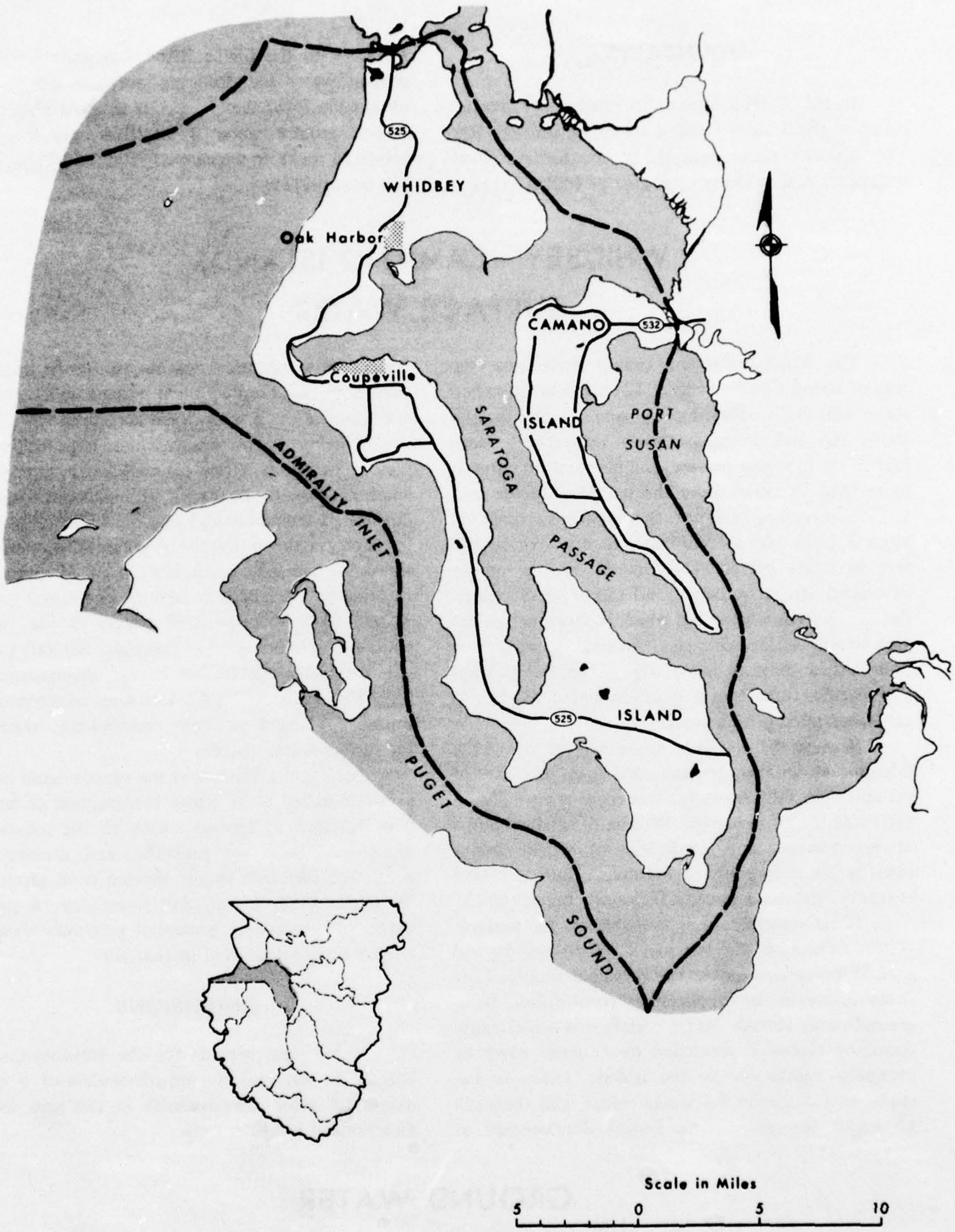


Figure 124. Whidbey—Camano Islands

known to occur at depths greater than 400 feet below sea level, and they are rarely found at depths greater than about 200 feet below sea level.

Quaternary deposits exposed at the surface are principally till and recessional outwash. Most of the upland areas are underlain by till, which is generally more than 20 feet thick and locally may be more than 200 feet thick. Because the till is composed largely of compacted fine materials, it is not an important aquifer, and it limits recharge to underlying aquifers. Till is overlain by isolated bodies of recessional outwash, which are usually less than 50 feet thick and are generally composed of fine sand and clay. Recessional outwash in the study area seldom contains significant amounts of water.

Aquifers are encountered at many intervals below till bodies, but the aquifers higher than sea level are generally perched with respect to those below them. The aquifers above sea level locally may exhibit either water-table or artesian conditions, but those below sea level are with rare exceptions artesian. These deeper aquifers are the ones most used because of their better yield characteristics.

Recharge to aquifers in the islands is by infiltration of precipitation on the land surface, and the estimated amount of recharge is about 10,000 acre-feet per year. Less than one-half, and perhaps as little as one-fourth of this amount penetrates till layers to reach the aquifers below sea level altitude.

The natural discharge of water in aquifers above sea level is mostly through seeps and springs along sea cliffs, and, to a smaller degree, along surface drainages. The natural discharge from aquifers below sea level is through submarine springs. Opportunities for artificial or induced recharge are not apparent.

Quality of Ground Water

Much of the ground water in the Whidbey-Camano Islands is considerably more mineralized than in most other places in the Study Area. Ground water having a dissolved solids content of about 100-300 ppm and a hardness generally less than 120 ppm is obtainable on southern Whidbey Island and in the upland areas of Camano Island. In other places, however, water hardness is considerably more than 180 ppm; and dissolved solids contents usually exceed 300 ppm. Most of the very hard water occurs north of Greenbank on Whidbey Island, and on Brown Point lowland of Camano Island. Abnormally high concentrations of chloride occur locally near Puget Sound, and may be the result of sea water encroachment. Scant data indicate that most of the ground water of the islands contains 30 to 40 ppm of silica. Objectionable amounts of iron are common locally in water pumped from both shallow and deep wells south and west of Clinton, in and near Freeland, south of Coupeville, and north and west of Penn Cove.

Utilization and Development

Ground water is used mostly for domestic needs which are served by small public-supply systems and by numerous small-capacity wells drilled for individual household and livestock use. All public-supply systems use ground water except the Whidbey Naval Air Station, which obtains its water from the Skagit River. Most irrigation use of ground water occurs in the lowland areas that are conducive to farming. Industrial use of ground water is mostly for food processing and for sand and gravel washing.

The larger-capacity wells are completed in aquifers deeper than sea level, and flowing-well conditions occur in these aquifers in low-altitude areas near Puget Sound. The largest well yield recorded in the islands is 600 gpm.

Owing to their more favorable water-bearing properties, the aquifers below sea level offer better opportunities for development than those above. However, apparent restriction of recharge to the lower aquifers would seem to limit their usefulness on a long-term basis. More significant is the vulnerability of these aquifers to salt-water encroachment.

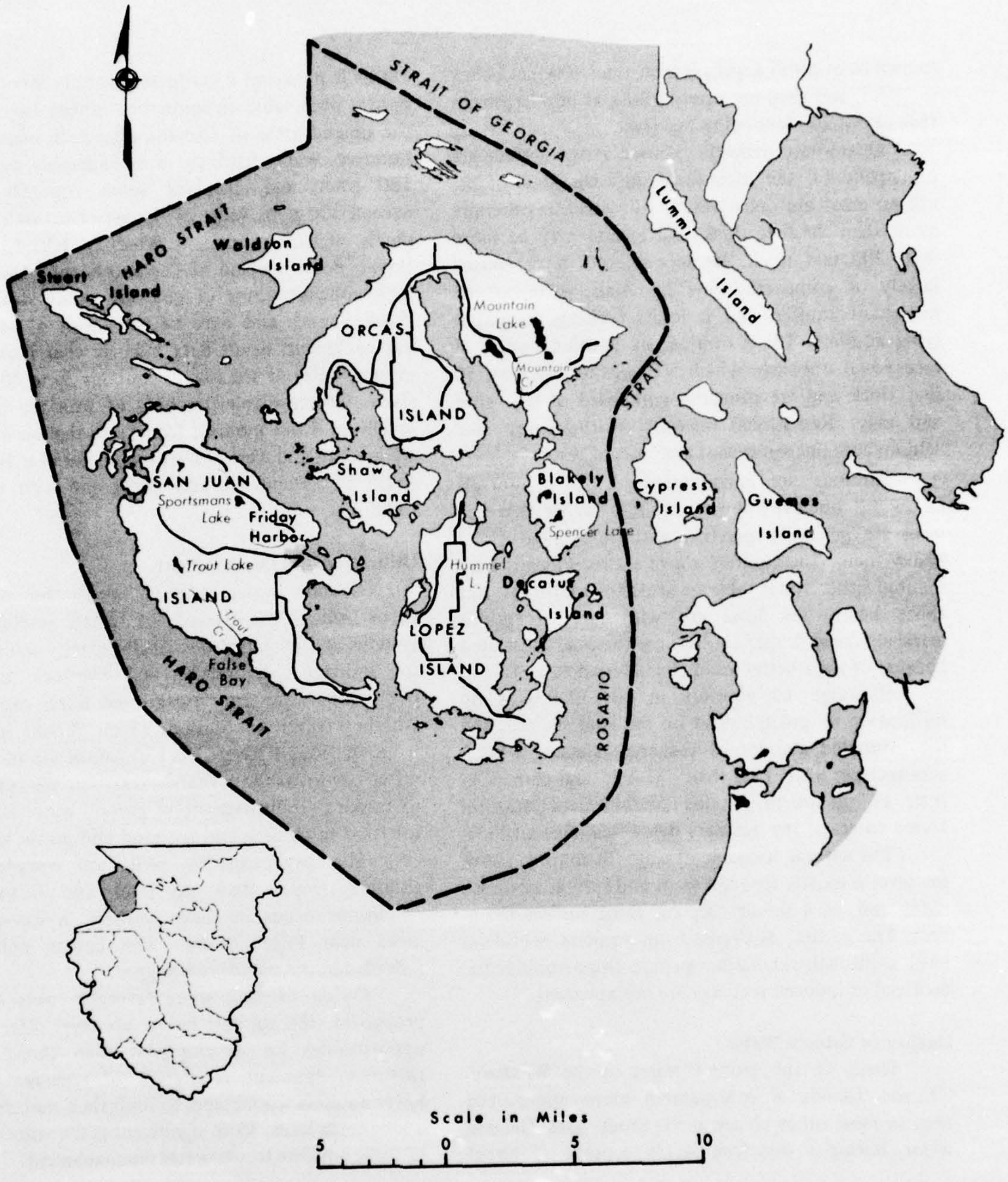


Figure 125. San Juan Islands

SAN JUAN ISLANDS

SURFACE WATER

The study area comprises San Juan County's islands and reefs, (Fig. 125), 175 of which are of sufficient importance to bear individual names. The surfaces of the islands are, in general, underlain by glacial drift through which numerous rocky knobs protrude. Shorelines are irregular, elevated, and rocky. Orcas Island, with an area of nearly 57 square miles, is the largest of the group and has the greatest relief. Mount Constitution, with a summit altitude of 2,409 feet, is on the northeastern part of Orcas Island and is the highest point in the islands.

Because of their location in the rain shadow of the Olympic Mountains and Vancouver Island uplands, the San Juan Islands receive little precipitation. Although there are no corroborating streamflow records, precipitation data indicate that average annual runoff ranges from about 5 inches in the southern areas to 15 inches in the northern areas. Only a few of the larger islands in the San Juan Islands are of sufficient size to support well-defined perennial stream systems; most of the drainages are characterized instead by ephemeral, or at best intermittent flows. The ephemeral streams exist in the predominately bedrock areas where there is little or no soil mantle to absorb and retain water. These drainages carry direct runoff from precipitation, which occurs primarily during the winter season; they are generally dry at other times. In areas with sufficient soil mantle on unconsolidated glacial deposits, ground-water contributions become a significant factor, and some streams in these areas are perennial. Their monthly runoff patterns are typical of other streams in the Puget Sound lowland whose summer base flows depend on ground-water contributions.

The small lakes and reservoirs on the islands cover 1.4 square miles; reservoirs that are used for municipal and irrigation purposes contain about 1,600 acre-feet of storage. The small size of watershed areas and the small runoff volumes preclude the liklihood of future significant storage projects. However about 285 ponds have been constructed on the San Juan Islands which have made a significant contribution to surface water supplies.

Because low flows of streams are supported by contributions from ground-water storage, surface water is probably similar in quality to ground water though perhaps less mineralized overall. Sanitary quality of lakes and streams may be locally impaired somewhat in populated areas as a result of sewage disposal.

Sediment problems are minor, and occur in localized areas of construction or farming. In some places, soils are eroded by rapid runoff from higher rocky areas.

DIVERSIONS

Because the San Juan Islands are incapable of supporting any large surface-water drainage systems, existing diversions are small with the exception of a diversion from Cascade Creek on the eastern end of Orcas Island.

Cascade Creek, one of the larger streams in the island group, serves as the outlet stream for both Mountain Lake and Cascade Lake. Part of the flow of Cascade Creek is diverted for domestic and irrigation use and hydroelectric power generation at Rosario Resort. This diversion, located about 1 mile below the Mountain Lake outlet, transfers waters from the Mountain Lake drainage to Cascade Lake, where it is stored and then released from the western end of the lake for use at the resort. In 1921 Moran deeded much of his lands to the state for development as Moran State Park but retained rights to the use of waters located on these lands for successors in interest to the Rosario Resort and remaining Moran estate. The new owners of Rosario have expanded the development, and in conjunction with the State Parks Department, have constructed a new diversion dam and a 16-inch diameter diversion pipeline.

The community of Olga maintains a claim to divert 2.2 cfs of water from this stream for domestic use. The water is diverted at the same reservoir dam as that used by Rosario Resort. The stream is dry most of the time below the Rosario diversion dam. The community of Doe Bay diverts as much as 0.5 cfs directly from the outlet of Mountain Lake for domestic needs. There is a pending application to divert an additional 1.5 cfs at this point for domestic use in the Deer Point area.

GROUND WATER

Ground-water supplies in the San Juan Islands seem barely adequate for individual household requirements even on a rural basis.

The better aquifers are in coarse Quaternary sediments, which cover about 60 square miles. Thickness of the Quaternary materials varies considerably, the maximum recorded being about 400 feet. However, in many places wells have been drilled through the entire Quaternary sequence without encountering aquifers adequate for domestic water supplies. Some wells are drilled as deep as 500 feet into the older consolidated rocks to obtain sufficient water.

Yields of wells completed in Quaternary aquifers rarely exceed 20 gpm; the largest yield recorded in the islands is 50 gpm. Aquifers in consolidated rocks generally are not capable of furnishing more than 10 gpm, although a well drilled in consolidated rock north of Friday Harbor is reported to have produced as much as 20 gpm.

The hardness of ground water is high; the highest measured water hardness is 274 ppm, in a very shallow well. Although a single sample, from a 168-foot well on Orcas Island, probably suggests that deeper aquifers contain softer water, none of the ground water can be used satisfactorily as a household supply without at least minimal treatment. Polluted water from shallow wells, possibly caused by sewage disposal in septic tanks, has been reported locally, but such incidents could be eliminated by proper sanitary measures.

TABLE 58.—Chemical and sanitary quality of surface water in the Puget Sound Study Area

[Results in parts per million, except as indicated]

Date		Water temperature (°C)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Nitrate (NO_3)	Phosphate (PO_4)	Dissolved solids	Hardness, as ($CaCo_3$)	Specific conductance (micromhos per cm at 25° C)	pH	Turbidity (Jackson turbidity units)	Dissolved oxygen	MPN[1]
Stillaguamish River near Silvana																		
July 1959	Max	22.8	10	3.5	3.3	1.1	48	4.4	2.8	2.0	0.10	58	39	96	7.5	400	14.3	1,500
to	Min	1.8	3.0	.5	.8	0	13	.9	0	0	0	17	11	26	5.9	0	8.4	0
May 1966	Mean	9.8	6.0	1.6	1.7	.5	26	3.0	1.3	.6	.02	37	21	53	7.1	50	11.1	205
	No.	80	79	79	79	79	79	79	79	72	72	79	79	79	79	44	80	80
Snohomish River at Snohomish																		
Aug. 1959	Max	19.0	7.2	1.6	3.1	.9	27	4.0	2.2	2.6	.12	40	22	57	7.3	160	14.0	24,000
to	Min	4.0	2.0	.2	.8	0	10	.8	.2	0	0	14	8	20	6.4	0	8.3	0
Apr. 1966	Mean	9.8	4.5	.9	1.8	.5	18	2.8	1.2	.8	.02	30	15	41	6.9	16	11.1	1,991
	No.	53	55	55	55	55	55	55	55	47	48	55	55	55	55	42	53	53
Puyallup River at Puyallup																		
Oct. 1960	Max	18.3	11	3.1	5.4	1.8	46	12	3.0	2.0	.13	74	40	112	7.5	85	12.4	24,000
to	Min	2.9	4.8	.8	2.2	.5	20	4.0	1.0	.1	.01	36	16	46	6.7	0	9.3	0
Apr. 1966	Mean	8.5	7.0	1.7	3.6	.9	29	6.9	1.6	.6	.05	55	24	69	7.0	25	10.9	5,224
	No.	31	35	35	35	35	35	35	35	28	28	35	35	35	35	12	31	31
Nisqually River at McKenna																		
July 1959	Max	20.0	7.5	2.4	4.2	1.3	41	5.2	2.8	.9	.19	61	28	79	7.5	25	12.8	2,400
to	Min	4.8	3.5	.8	2.3	.3	18	1.4	0	0	0	37	12	37	6.2	0	8.6	0
Mar. 1966	Mean	9.4	5.7	1.4	3.1	.6	27	2.6	1.7	.3	.04	47	20	55	7.1	12	11.2	200
	No.	34	35	35	35	35	35	35	35	33	33	35	35	35	35	16	33	34
Dosewallips River at Brinnon																		
July 1959	Max	15.5	18	2.0	3.3	.6	56	8.4	1.5	.4	.10	72	52	114	7.9	80	13.6	230
to	Min	3.9	8.5	.2	.9	0	27	4.2	.2	0	0	38	24	57	6.9	0	10.0	0
Feb. 1966	Mean	8.6	14	1.1	1.7	.2	43	6.2	.8	.2	.02	53	38	86	7.5	12	11.2	30
	No.	27	28	28	28	28	28	28	28	27	27	28	28	28	28	10	26	28
Big Quilcene River near Quilcene																		
July 1959	Max	15.6	18	2.9	7.8	0.4	52	3.4	21	1.0	0.32	94	57	158	7.8	5	13.5	430
to	Min	3.6	9.0	1.1	1.6	0	36	1.6	2.0	0	0	43	30	72	6.8	0	9.8	0
Feb. 1966	Mean	8.7	13	2.0	3.6	.2	45	2.4	6.8	.2	.03	63	40	99	7.4	2	11.4	44
	No.	27	28	28	28	28	28	28	28	27	27	28	28	28	28	10	26	28
Goldsborough Creek at Shelton																		
Nov. 1964	Max	17.0	27	11	4.6	.6	128	9.8	6.2	1.1	.13	151	113	227	8.2	29	12.5	4,600
to	Min	4.5	4.8	1.8	2.0	.1	21	2.4	1.5	.3	0	40	20	49	6.8	0	8.3	36
May 1966	Mean	9.6	15	6.1	3.5	.4	72	5.3	3.1	.5	.05	90	63	135	7.4	9	10.7	900
	No.	19	20	20	20	20	20	20	20	12	12	20	20	20	20	12	19	19
Chico Creek near Bremerton																		
Nov. 1964	Max	12.1	9.2	3.4	3.4	.6	45	3.6	2.5	2.7	.08	59	36	86	7.7	10	10.6	2,400
to	Min	11.8	5.2	1.7	2.0	.2	24	.4	.5	.5	.01	36	20	49	6.9	0	10.1	430
Apr. 1966	Mean	12.0	7.3	2.6	2.9	.3	35	2.7	1.8	1.2	.04	49	29	70	7.2	4	10.4	1,415
	No.	2	14	14	14	13	14	14	14	13	8	14	14	14	14	8	2	2
Elwha River at McDonald Bridge near Port Angeles																		
July 1959	Max	15.5	16	1.7	2.3	.6	51	9.2	1.0	.3	.11	67	46	106	8.0	60	14.1	430
to	Min	3.2	10	.1	1.2	0	32	4.9	0	0	0	42	29	63	6.4	0	10.0	0
Feb. 1966	Mean	9.0	13	1.0	1.8	.2	41	7.5	.7	.1	.02	54	38	86	7.5	12	11.6	24
	No.	28	28	28	28	28	28	28	28	26	27	28	28	28	14	14	26	28
Dungeness River near Sequim																		
July 1959	Max	16.1	23	3.9	4.1	.6	79	10	2.2	.6	.06	94	69	152	7.9	65	13.4	230
	Min	2.4	12	1.2	1.6	0	44	4.4	.2	0	0	50	37	80	7.2	0	8.5	0
Feb. 1966	Mean	9.0	17	2.3	2.7	.3	60	7.2	1.1	.2	.01	70	52	116	7.6	10	11.2	43
	No.	28	28	28	28	28	28	28	28	27	27	28	28	28	28	10	26	28
Nooksack River at Ferndale																		
Oct. 1961	Max	17.5	13	4.9	4.2	1.0	53	15	4.2	2.5	0.05	77	53	128	7.7	700	13.6	24,000
to	Min	2.0	5.0	1.4	1.2	.2	22	5.4	.2	.1	0	32	22	51	6.8	5	5.1	36
May 1966	Mean	8.8	9.6	3.0	2.5	.6	36	9.2	1.9	.8	.02	57	36	86	7.2	69	11.1	2,126
	No.	53	54	54	54	54	54	54	54	45	46	34	54	54	54	45	53	53
Samish River near Burlington																		
July 1959	Max	19.0	12	4.3	4.2	1.4	52	7.1	4.0	4.7	.09	71	44	106	7.7	90	13.0	11,000
to	Min	3.8	4.8	1.1	1.7	.2	15	3.8	.2	.7	0	34	17	52	6.6	0	7.0	0
Mar. 1966	Mean	9.7	7.4	2.2	2.8	.7	30	4.8	2.2	2.2	.03	49	27	71	7.1	21	10.8	1,022
	No.	35	35	35	35	35	35	35	35	33	33	35	35	35	35	16	35	35

TABLE 58.—Continued

Date		Water temperature (°C)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Nitrate (NO_3)	Phosphate (PO_4)	Dissolved solids	Hardness, as ($CaCO_3$)	Specific conductance (micromhos per cm at 25° C)	pH	Turbidity (Jackson turbidity units)	Dissolved oxygen	MPN[1]
Skagit River at Marblemount																		
July 1959 to Mar. 1966	Max	15.2	10	1.4	1.2	.9	35	5.2	.5	1.1	.08	44	30	70	8.0	5	13.1	230
	Min	3.8	4.5	.1	.6	.2	16	2.8	0	0	0	23	14	32	6.8	0	9.7	0
	Mean	8.0	7.6	.8	.8	.5	26	4.0	.1	.3	.01	33	22	51	7.3	2	11.7	43
	No.	35	35	35	35	35	35	35	35	33	33	35	35	35	35	15	35	35
Skagit River near Mount Vernon																		
July 1959 to May 1966	Max	17.8	10	2.2	2.0	1.0	38	5.6	1.5	1.5	.07	52	32	76	8.1	350	13.7	24,000
	Min	4.0	4.5	.3	.7	.2	18	2.0	0	0	0	22	15	36	6.3	0	9.3	0
	Mean	9.1	7.0	1.2	1.2	.6	26	4.2	.4	.4	.02	35	22	53	7.2	23	11.2	1,909
	No.	80	81	81	81	81	81	81	81	73	73	81	81	81	81	44	81	80
North Fork Stillaguamish River near Arlington																		
Nov. 1961 to Mar. 1966	Max	17.6	10	2.8	2.9	.9	44	3.6	2.5	1.0	.04	55	34	80	7.6	135	13.4	930
	Min	2.3	3.0	.9	1.0	.2	14	1.8	.5	.1	0	22	12	29	6.7	0	9.3	0
	Mean	8.5	6.0	1.6	1.7	.5	26	2.8	1.2	.6	.02	36	22	52	7.2	42	11.5	178
	No.	17	17	17	17	17	17	17	17	13	15	17	17	17	17	14	17	17

[1] Most probable number of coliform organisms per 100 ml.

TABLE 59.—Temperatures of streams in the Puget Sound Study Area

Site	Records analyzed		Observed temperature ranges (°F)[1]												
	Spot observations	Thermograph	[2]	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Nooksack-Sumas Basins															
Nooksack River near Deming	Oct 1944-July 1965	None	Max	40	42	46	48	52	54	62	65	58	50	46	43
			Min	32	33	33	38	43	43	47	48	48	42	35	36
			N	14	8	15	12	13	13	10	13	14	11	15	11
South Fork Nooksack River near Wickersham	Oct 1944-July 1965	None	Max	40	43	44	49	50	61	70	68	61	52	45	41
			Min	32	35	34	39	42	42	45	53	50	41	34	32
			N	17	11	18	16	14	16	12	15	16	15	14	15
Nooksack River below Cascade Creek near Glacier	Oct 1944-June 1965	None	Max	38	42	43	45	48	52	52	59	53	46	42	40
			Min	32	34	33	37	39	39	41	45	44	39	34	34
			N	16	9	17	12	17	15	12	16	18	14	16	13
Nooksack River near Lynden	Jan 1945-Aug 1966	None	Max	43	44	44	49	54	58	62	66	60	51	49	42
			Min	32	34	32	39	43	44	47	48	49	44	36	33
			N	15	6	19	12	15	14	13	16	18	13	13	14
Skagit-Samish Basins															
Skagit River above Alma Creek near Marblemount	Dec 1950-Jan 1953	Jan 1953-Sep 1965	Max	43*	43*	44*	46*	48*	53*	56*	55*	53*	53*	50*	47
			Min	36*	36*	35*	38*	40*	44*	46*	48*	47*	45*	39*	39*
			N	2	1	2	1	2	1	1	1	1	2	1	3
Cascade River at Marblemount	Dec 1944-Mar 1952	May 1952-Aug 1965	Max	41*	44*	51*	49*	51*	59*	58*	58*	56*	53*	47*	42*
			Min	32	32*	33*	38*	39*	40	42*	43*	42*	40	32*	34
			N	6	8	3	5	7	4	5	5	3	7	4	5
Skagit River near Mount Vernon	Sep 1944-June 1962	July 1962-Sep 1965	Max	44	44	53	50*	55*	56*	64	62*	61*	58	51*	45*
			Min	33	38	34	39	43	44	46	52	50	46	38*	36*
			N	12	9	9	10	15	13	11	11	12	14	8	11
Samish River near Burlington	Aug 1943-July 1965	None	Max	44	46	57	55	61	64	68	68	60	54	49	48
			Min	38	32	37	38	44	52	51	54	49	45	35	36
			N	13	14	17	15	18	14	15	20	20	19	18	15
Stillaguamish Basin															
South Fork Stillaguamish River near Granite Falls	Dec 1944-Aug 1965	None	Max	42	43	43	49	50	61	62	69	63	57	47	43
			Min	32	35	34	40	38	42	49	52	47	45	35	36
			N	14	14	17	17	14	12	12	14	16	17	12	11
Jim Creek near Arlington	None	Oct 1951-Apr 1957	Max	42*	44*	48*	53*	62*	66*	73*	69*	64*	59*	50*	46*
			Min	33*	33*	35*	39*	42*	46*	50*	53*	50*	44*	32*	33*
North Fork Stillaguamish River near Darrington	June 1950-Feb 1952	Mar 1952-Sep 1957	Max	41	41*	45*	47*	51*	55*	61*	63*	70*	54*	47*	45*
			Min	36*	36*	37*	39*	41*	43*	45*	49*	47*	43*	38*	35*
			N	2	1	1	1	1	1	1	2	3	0	2	1

TABLE 59.—Continued

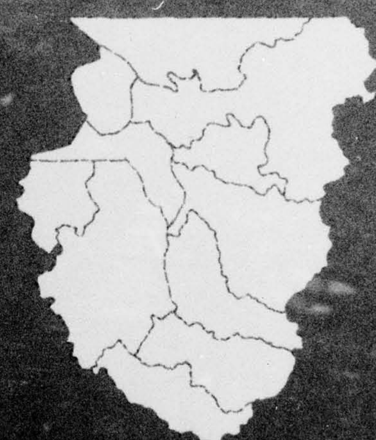
Site	Records analyzed: Spot observations	Records analyzed: Thermograph	[2]	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
				Observed temperature ranges (°F)[1]											
Pilchuck Creek near Bryant	June 1950-Jan 1952	Mar 1952-Sep 1965	Max	44*	44*	46*	55*	70*	78*	82*	76*	70	59*	51*	46*
			Min	33*	33*	33*	37*	41*	45*	48*	53*	48*	43*	36*	36*
			N	2	1	1	1	1	2	2	2	2	0	2	1
Snohomish Basin															
Skykomish River near Gold Bar	Nov 1944-Aug 1965	None	Max	40	41	45	49	48	54	59	67	61	54	47	49
			Min	32	33	36	40	41	41	45	50	50	43	38	35
			N	16	13	17	16	16	14	14	12	14	15	17	12
Wallace River near Gold Bar	July 1946-June 1955	July 1955-Sep 1965	Max	44*	45*	47*	52*	58*	64*	68*	70*	66*	60*	50*	46*
			Min	32	32*	34*	37*	40*	43*	47*	49*	46*	42*	34*	32*
			N	7	6	9	7	7	8	9	9	5	7	9	6
Woods Creek near Monroe	July 1946-Aug 1965	None	Max	45	43	47	57	58	59	66	69	62	54	49	47
			Min	33	36	40	41	48	47	55	55	50	45	38	33
			N	13	13	14	16	18	17	18	18	15	14	17	15
Tolt River near Carnation	Nov 1944-July 1965	None	Max	44	48	44	49	51	54	68	66	60	54	46	47
			Min	32	39	39	40	42	43	43	52	49	42	38	39
			N	16	14	13	18	13	17	15	13	14	14	14	11
Snoqualmie River near Carnation	Nov 1945-Aug 1965	None	Max	44	44	48	51	54	58	68	74	62	60	51	45
			Min	34	32	39	40	44	45	51	57	49	42	37	39
			N	18	12	17	15	12	13	15	14	12	12	16	12
Quilceda Creek near Marysville	July 1946-July 1965	None	Max	45	48	48	55	62	68	60	62	64	57	48	47
			Min	34	32	38	43	49	51	52	54	52	43	40	34
			N	14	14	16	18	14	9	15	14	16	21	13	7
Cedar-Green Basins															
Green River near Palmer	Nov 1944-June 1963	None	Max	40	41	44	53	50	54	65	62	62	56	46	44
			Min	34	32	36	38	41	42	47	52	46	45	34	35
			N	15	14	11	12	16	14	14	17	17	14	16	11
Green River near Auburn	Nov 1944-Feb 1952	Mar 1952-Feb 1965	Max	47*	48*	50*	55*	65*	73*	75*	71*	67*	62*	51*	48*
			Min	35*	33*	37*	41*	44*	48	52*	51	46	44*	38*	33*
			N	3	5	7	4	5	4	7	2	7	5	5	6
Sammamish River at Bothell	Oct 1944-Aug 1963	None	Max	44	45	49	61	62	64	74	67	68	60	50	46
			Min	37	38	40	39	51	49	53	55	55	47	40	36
			N	17	15	11	18	11	11	18	11	15	10	13	13
Cedar River near Landsburg	Nov 1944-July 1953	Aug 1953-Sep 1965	Max	45*	46*	47*	51*	58*	61*	67*	64*	60*	54	50*	46*
			Min	35	33	37*	42	44*	46*	49*	50*	48	45*	50*	38*
			N	6	1	7	5	7	6	4	8	5	6	6	7
Cedar River at Renton	Aug 1945-Oct 1965	Aug 1965-Oct 1965	Max	45	45	47	50	57	62	66	66*	63*	58	51	47
			Min	33	38	40	41	46	51	52	53*	49	44	41	39
			N	17	16	17	12	14	17	15	19	15	17	19	12
Puyallup Basin															
Puyallup River near Orting	Oct 1944-Aug 1965	None	Max	43	45	44	48	58	58	59	59	59	57	47	44
			Min	32	34	37	40	44	45	48	45	48	41	33	32
			N	22	24	21	21	22	18	17	17	16	23	21	19
White River near Sumner	Mar 1945-Aug 1965	None	Max	47	47	49	63	64	64	72	73	66	57	51	49
			Min	34	38	37	41	43	47	52	56	54	46	40	36
			N	16	14	21	14	16	23	18	15	19	17	18	18
Puyallup River near Puyallup	Nov 1944-Oct 1964	Aug 1965-Sep 1965 Oct 1967-Nov 1967	Max	44	46	48	56	59	61	63	64*	64*	57*	49	44
			Min	32	32	39	46	48	50	52	50*	47*	42*	38	36
			N	15	11	21	14	10	18	10	12	14	15	16	12
Nisqually-Deschutes Basins															
Deschutes River near Rainier	July 1949-Nov 1964	None	Max	46	48	47	54	59	61	70	66	58	54	48	47
			Min	38	35	40	42	45	50	53	56	50	46	39	40
			N	10	11	16	9	16	10	15	14	12	14	14	12
Deschutes River near Olympia	June 1945-Aug 1964	None	Max	47	49	50	56	58	66	68	65	63	56	49	47
			Min	36	36	39	44	46	53	54	54	54	46	42	37
			N	12	13	13	12	13	12	13	15	12	11	15	10
Woodland Creek near Olympia	July 1949-Aug 1965	None	Max	46	48	49	53	61	59	58	62	57	53	50	48
			Min	39	40	41	47	50	52	52	49	48	47	44	40
			N	13	10	15	12	12	12	12	13	12	14	18	8
Nisqually River near National	Oct 1944-Sep 1951	Oct 1952-Sep 1965	Max	46*	43*	48*	52*	58*	60*	65*	61*	60*	55*	49*	44
			Min	32*	32*	32*	37*	38*	40*	41*	44*	41*	36	33*	35*
			N	5	2	4	6	4	4	5	2	6	5	1	4
Mineral Creek near Mineral	Jan 1945-July 1951 Oct 1957-July 1965	Aug 1951-Sep 1957	Max	44	43*	47	53*	61*	64*	73*	70*	66*	60*	50*	44*
			Min	32	33*	34*	39*	41*	46	50*	51*	49*	42	35*	35*
			N	12	10	12	9	13	11	10	7	12	15	4	11
Nisqually River at LaGrande	Oct 1959-Feb 1965	Mar 1965-Sep 1965	Max	42	42	51	44	53	48	49	53	62	54	48	41
			Min	38	37	39	40*	39*	42*	42*	43*	46*	49	45	41
			N	5	5	3	4	4	4	1	5	4	5	4	2
Nisqually River near McKenna	Jan 1945-July 1963	None	Max	43	43	46	48	49	57	60	61	64	58	49	45
			Min	35	35	40	41	44	48	51	52	52	49	41	38
			N	12	14	14	11	14	13	14	10	15	14	11	14

TABLE 59.—Continued

Site	Records analyzed			Observed temperature ranges (°F)[1]											
	Spot observations	Thermograph	[2]	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
West Sound Basins															
Snow Creek near Maynard	June 1952-Aug 1965	None	Max	44	47	44	48	57	56	68	66	60	53	50	46
			Min	32	35	35	43	40	49	50	53	50	44	40	34
			N	11	10	8	12	11	12	14	13	10	10	10	10
Little Quilcene River near Quilcene	July 1951-Dec 1957	None	Max	42	44	44	48	53	51	63	56	55	49	50	46
			Min	38	38	37	44	45	48	52	52	48	46	41	39
			N	4	5	4	4	5	3	5	7	6	5	5	6
Duckabush River near Brinnon	Oct 1944-Nov 1965	None	Max	42	41	48	48	48	53	55	56	54	50	47	45
			Min	35	32	38	39	40	42	45	49	47	43	39	37
			N	15	12	20	16	17	13	16	16	16	15	10	17
Hamma Hamma River near Eldon	Aug 1951-Dec 1965	None	Max	42	42	43	44	51	49	53	56	52	49	48	46
			Min	38	33	37	38	41	44	46	48	47	42	36	38
			N	11	7	13	11	9	8	12	14	14	9	11	9
North Fork Skokomish River below Staircase Rapids near Hoodsport	Oct 1944-Nov 1965	Apr 1965-Sep 1965	Max	41	41	40	45	48	58	58	57*	54	59	45	42
			Min	33	32	36	39	40	41	44	48	46	41	38	38
			N	14	13	17	15	13	15	16	14	15	16	14	16
North Fork Skokomish River near Potlatch	Oct 1944-Jan 1965	Mar 1965-Sep 1965	Max	45	48	49	55*	60*	65	68	64	65	59	49	49
			Min	40	32	39	43*	45*	50	52*	51*	49*	42	41	39
			N	5	11	11	6	7	8	9	7	8	11	7	7
South Fork Skokomish River near Hoodsport	Sep 1963-Aug 1964	Oct 1964-Sep 1965	Max	39*	40*	43*	45*	48*	55*	57*	56*	53*	48*	45*	43
			Min	34*	37*	39*	39*	40*	43*	46	49	47*	44*	39	35*
			N	1	0	1	1	0	1	1	1	1	1	1	1
South Fork Skokomish River near Potlatch	Sep 1945-Apr 1955	May 1955-Sep 1964	Max	44*	45*	46*	51*	56*	63*	66*	66*	61*	57*	49*	45*
			Min	35*	34	32*	38*	41*	42*	46*	48*	47*	42*	36*	33*
			N	6	6	5	8	5	6	10	6	8	6	4	4
Vance Creek near Potlatch	None	July 1955-Sep 1957	Max	42*	42*	42*	51*	61*	62*	64*	61*	60*	53*	45*	43*
			Min	35*	34*	33*	42*	42*	44*	51*	50*	47*	41*	34*	33*
Skokomish River near Potlatch	Oct 1944-Apr 1955	May 1955-Sep 1965	Max	45	46	49	52*	58*	64*	69*	61*	59*	54*	53*	47*
			Min	35*	35*	34*	39*	40*	43*	47*	50*	48*	44*	40*	38*
			N	7	9	9	7	10	7	6	7	9	11	8	6
Weaver Creek near Potlatch	None	Apr 1955-Sep 1959	Max	49*	49*	50*	53*	54*	54*	54*	54*	54*	52*	51*	50*
			Min	40*	41*	40*	42*	43*	45*	45*	45*	44*	44*	40*	41*
Purdy Creek near Union	Sep 1954-Apr 1955	May 1955-July 1960	Max	46*	48*	51*	53*	54*	55*	54*	54*	53*	51*	49*	47*
			Min	38*	40*	38*	45*	47*	49*	50*	50*	47*	45*	39*	38*
			N	1	0	1	1	0	0	0	0	1	2	2	2
Union River near Belfair	July 1947-July 1959	None	Max	45	46	49	52	59	57	58	59	54	54	48	47
			Min	37	38	41	45	48	48	52	51	48	40	44	38
			N	10	9	9	10	10	10	12	12	9	10	8	10
Gold Creek near Bremerton	Dec 1945-Aug 1965	None	Max	44	46	48	52	62	65	66	62	60	54	47	45
			Min	33	36	35	44	50	53	53	50	50	40	39	38
			N	18	15	18	16	16	14	16	17	17	13	18	10
Tahuya Creek near Bremerton	May 1945-Oct 1956	None	Max	45	43	49	49	56	62	60	59	57	53	49	45
			Min	35	34	35	43	47	48	52	52	50	40	41	40
			N	9	9	9	6	12	9	8	10	12	8	9	8
Dewatto Creek near Dewatto	July 1947-May 1952, Oct 1959-Aug 1965	None	Max	45	50	46	54	54	55	58	58	55	54	49	45
			Min	32	34	38	42	47	49	50	53	51	44	41	32
			N	7	8	11	10	7	8	9	10	6	12	9	4
Dogfish Creek near Poulsbo	July 1947-July 1965	None	Max	45	46	47	51	58	56	59	61	54	54	48	46
			Min	37	38	38	44	49	50	52	51	50	46	41	33
			N	15	13	14	12	14	12	16	18	17	12	19	12
Huge Creek near Wauna	July 1947-June 1965	None	Max	46	47	48	49	57	57	61	61	54	55	47	47
			Min	37	39	39	44	49	48	44	51	48	42	41	36
			N	16	13	17	14	13	12	14	18	12	15	14	13
Goldsborough Creek near Shelton	June 1951-Sep 1961, Nov 1959-July 1965	None	Max	44	47	45	51	53	58	62	59	57	52	48	46
			Min	38	41	43	47	52	52	57	57	49	51	40	39
			N	5	6	5	4	4	7	7	5	5	4	6	6
Elwha-Dungeness Basins															
Elwha River near Port Angeles	Oct 1944-Oct. 1964	None	Max	42	45	44	47	50	56	57	63	59	55	46	44
			Min	35	35	36	40	40	45	45	47	51	44	39	37
			N	14	14	12	14	14	14	14	16	9	18	10	16
Dungeness River near Sequim	Oct 1944-Dec 1964	None	Max	45	48	44	46	46	50	56	56	55	51	45	41
			Min	32	36	37	38	40	43	45	48	46	40	35	35
			N	16	15	12	14	12	14	15	18	12	16	11	19

[1] Temperatures obtained from thermograph records are indicated by "*".
[2] Maximum and minimum observed temperatures, and number of spot observations that were used in analysis.

Need for Additional Hydrologic Information



NEED FOR ADDITIONAL HYDROLOGIC INFORMATION

The foundation of a water resources program includes the collection of essential basic data, and scientific analysis and interpretation of these data to determine hydrologic characteristics of the surface and ground-water reservoirs, and an evaluation of the best methods for development and management of the water to meet anticipated uses. Therefore, information submitted in this appendix has been obtained from numerous sources and represents several different types of hydrologic, climatic, and geologic data, to provide a general picture of the region's water resources. Because the present information is incomplete, however, and does not include data that will be required for any future regional planning program, the following summary defines those areas of surface and ground-water hydrology where additional studies and analyses are recommended.

In addition to the potential storage sites listed, there are probably numerous additional sites for storage of 5,000 or more acre-feet, and a large number of sites less than 5,000 acre-feet in capacity which in the aggregate could contribute greatly to water storage or stream regulation. The need for storage to meet requirements for municipal industrial water irrigation, reducing flood damage or maintaining minimum flows should be a consideration in the study of these sites.

CLIMATOLOGY

Additional climatological data are needed to define the climate of the entire Puget Sound area in more detail. In 1967, about 35% of the temperature and precipitation stations are less than 100 feet above sea level, 60% are less than 500 feet, 80% are less than 1,000 feet, and 90% are less than 2,000 feet. This distribution provides a fair coverage in most lowland areas but is inadequate in the foothills and mountains. As a rule, stations have been limited to locations where people are available to serve as cooperative weather observers. This limitation, by necessity, has placed most of the reporting points along highways crossing the Cascades or in areas where power companies, Forest Service, timber companies, and others maintain year-around operations. To establish an adequate network of stations, equipment must be developed and installed that will operate unattended for extended periods and that can be interrogated by radio or telephone.

All stations (1967) recording wind data, except the one at Stampede Pass, are in the lowlands near Puget Sound. Additional information is needed regarding winds in the mountain valleys and on mountain ridges.

The only two evaporation stations in the Puget Sound Study Area are in the lowlands near the Sound. Evaporation measurements are needed in timbered areas along the slopes of the mountains as well. Also, data are needed on evaporation losses from lakes and reservoirs in the mountains and at other places distant from the Sound.

Solar radiation measurements have been made only in the Seattle area. Information on radiation in the "rain shadow" of the Olympic Mountains and in other areas at higher altitude in the Cascades and Olympics is desirable.

Climatological data collected since 1948 have been filed on punch cards for computer summarization. Data collected prior to 1948 also should be processed. By using advanced statistical techniques and modern computers, frequency distributions of specific events and expected return periods, based on long-term records, can be prepared.

SURFACE-WATER RESOURCES

The existing stream-gaging network should be expanded to provide a better foundation for any future water-development and management programs. The majority of gaging stations are on the larger rivers, and very few are located where they measure runoff from smaller watersheds. In addition, no continuous records of runoff are available for streams that drain any of the numerous islands in the Puget Sound Area.

Because of the need to determine the yields of smaller streams, both for local use and for their individual contributions to larger streams, there is an increasing need for streamflow data from small watersheds. Such data on the smaller streams would

also allow evaluation of flood discharge and routing, and design of local water-control and highway structures in these areas. Upstream watersheds will also increase in importance as sources of potential water supply as water use increases in lower areas. Because not every upstream watershed can be effectively gaged, however, reliable procedures should be instituted for estimating water yields by indirect methods.

Analytical and interpretive studies should be made of climatic, physiographic, and geologic characteristics that determine basin yield. Land use, cultural practice, and methods used for watershed protection programs should be critically evaluated relative to their effects on the natural basin runoff. Studies of the smaller river basins should be undertaken to define in detail both the local hydrologic systems and their relation to the larger watershed.

Deficiencies in streamflow data are particularly great for small areas at higher altitudes; above 4,000 feet, for example, data are being collected at only three sites, as part of a glaciological research program. Because of the large quantities of water stored in glaciers following winter snowfall, and subsequent release of a part of this water as summer snowmelt, additional knowledge is needed of the hydrologic budget of the ice masses and of the physics of snowmelt. Procedures should be developed for evaluating the snow-water resources and for predicting amounts and regimen of flows to be expected. Glaciological data can supplement existing snow-survey computations to assist in evaluating summer streamflow that would be available for downstream municipal and irrigation supplies and for operation of hydroelectric powerplants.

Flood-frequency studies for some streams should be updated to include 10 years of data that have not been analyzed as of 1967. In addition, the flood data obtained at the many crest-stage gages should be used to define flood characteristics in small watersheds; definition of these characteristics has not been possible from previous flood-frequency studies.

In the past, emphasis has been placed on the study of floods. With increasing competition for water, however, studies of low flows will become more and more important. An increase in low-flow frequency studies would provide a basis for the design of water-supply and waste-disposal systems, for the maintenance of restricted channel discharges, and for a definition of the amount of water available for fish propagation and supplemental irrigation.

A better understanding of the principles of tidal flow is vitally important in this region of many tidal estuaries. Rates of fresh-water discharge, flushing, salinity intrusion, and many other tidal-flow characteristics must be determined to resolve problems that arise with the increased use and development of tidal estuaries.

Most aspects of surface-water quality will become less and less desirable with the increasing development and use of water. Many consumptive and nonconsumptive uses cause deterioration in water quality because they involve discharge of a great variety of wastes. Better definition of the existing water quality is needed as well as expansion of water quality monitoring networks. This expansion should include collection of data for many of the smaller streams.

Dispersion and time-of-travel studies have been made on the Duwamish River because of local pollution problems. These and similar investigations on four other major streams for the current planning study illustrate the need and usefulness of such information as streams receive ever-increasing volumes of domestic and industrial wastes. Future time-of-travel and dispersion investigations should be expanded to include other principal streams in the region and should consist of shorter reaches than were examined for the present study. In addition, the investigations should be repeated periodically to evaluate the effects of various discharge rates and channel modifications on dispersion and time of travel.

A systematic program is also needed for obtaining water temperatures on a continuous basis, generally on streams that are important for fish propagation, but particularly on streams where a high degree of development and use has occurred or is anticipated. Analyses and evaluation of water-termperature data that have been collected in the past will greatly increase the value of these data. One of the results of the current planning study was to emphasize deficiencies in the available temperature data and the need to establish an effective network for continuous recording of water temperatures.

Probably the least studied of hydrologic factors in the Study Area is that which defines the amount, character, and rates of sediment yield from the drainage basins. A collection of data on sedimentation has been recently initiated by a reconnaissance project that defines sediment characteristics in the

Snohomish River Basin. Sediment-sampling stations have been operated for very short periods, however, and long-term continuous records throughout the Study Area are needed to reflect trends in sediment transport. Also, the nature of fluvial sediments of all streams in the region needs to be interpreted, relative to the geologic origin of the sediment and to the mode and areas of their deposition in the watershed. Flow and sedimentation adjust to natural stream channels, but alteration of these characteristics by control works may have beneficial or detrimental effects, depending upon local channel conditions.

GROUND-WATER RESOURCES

For proper development and management of the region's ground-water resources, more information is needed than is presently available, particularly in the Skagit and Elwha-Dungeness Basins, and in the area between Port Townsend and Quilcene in the West Sound Basins. Detailed ground-water investigations that include geologic mapping should be made in these areas to identify geologic units and the water-bearing characteristics of the aquifers contained within them. Although ground-water withdrawal in the study area probably can be increased considerably beyond that of the present, development of local ground-water supplies should be planned only on the basis of quantitative field investigations that would incorporate exploratory drilling and aquifer testing. Such drilling and testing would permit a determination of hydraulic constants and an evaluation of the potential yield of the ground-water reservoir.

As the ground-water reservoir in a given basin undergoes development, periodic measurements of water levels and chemical analyses of water samples are advisable for early detection of problems that might occur during the course of development. To collect such data effectively, a network of observation wells that are accessible for periodic sampling and water-level measurements should be established and maintained. Wells included in the observation program should be selected so as to reflect representative changes in water levels and chemical quality that might result from ground-water development of various aquifers and local areas. In areas near the coast an observation-well system is currently being established for identifying water-quality changes that would detect inland movement of the interface between fresh and salt water. Also, because of the possibility that domestic sewage and industrial waste may contaminate shallow aquifers which, in turn, may pollute nearby streams, water-quality changes in these aquifers should be evaluated periodically.

In addition to the data obtained from the observation well network, newly drilled production wells can supply a large quantity of additional information, such as pump-test data, well-completion data, drillers' logs, and chemical analyses. All this information should be collected and filed systematically at a central location, so that it can be used interpretively by water-management and development agencies, and by the interested public.

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